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Confronting Energy, Food, and Climate Challenges – Analyzing Tradeoffs in Agriculture and Land Use Change

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Abstract

Maintaining and improving future food and energy security poses key challenges globally, especially in the face of climate change and climate mitigation. a computable general equilibrium (CGE) model -- the Applied Dynamic Analysis of the Global Economy model focusing on agriculture and land use (ADAGE-ALU), is used to examine how the global economy, especially energy, agriculture and land use, responds when facing these challenges. Despite continued increases in land productivity and energy efficiency in future decades, the effects of population and economic growth would dominate, leading to global increases in agricultural production, but also rising food and energy prices as well as continually growing GHG emissions in the *BAU* scenario. Comparing the climate change scenario with the *BAU* scenario, there are substantial reductions in global crop production and significant further increases in food prices, but little change in fossil fuel and biofuel production and energy prices, and only mild increases in CO_2 emissions due to land-use changes. Relative to the *BAU* case, the implementation of a carbon tax on emissions other than those from land use change leads to the expansion of global biofuel production and a shift in the mix of crops produced towards those used as biofuels feedstocks, raises food prices, and reduces oil consumption and price slightly. Meanwhile, GHG emissions are slightly reduced as a result of lower oil consumption. In the *REDD* scenario, some cropland is afforested to store carbon, leading to a moderate rise in food and energy prices and significant GHG emission reductions. When climate change, *REDD* scenarios are implemented together, we see even higher reductions in global crop production and larger food price increases, along with greater reduction in GHG emissions compared with the *CC* scenario.

Key words: Biofuels, Computable General Equilibrium, Carbon tax, Food security, GHG Mitigation

Confronting Energy, Food, and Climate Challenges – Analyzing Tradeoffs in Agriculture and Land Use Change

1. Introduction

Maintaining and improving future food and energy security poses key challenges globally, especially in the face of climate change and climate mitigation. Global food and energy demand are expected to increase substantially in coming decades due to population and income growth. While agriculture and forestry can provide feedstocks for future energy production, the use of land to produce biomass for energy generation competes with demand for land to produce food, feed, and fiber. Simultaneously, agriculture is threatened under climate change, facing expected reductions in global productivity that will increase competition for land resources. Meanwhile, forestland is a carbon sink and an option to mitigate climate change. The combination of these key factors raises questions on how to balance the tradeoffs to enhance food and energy security and reduce greenhouse gases (GHG) emissions. In this study, a computable general equilibrium (CGE) model -- the Applied Dynamic Analysis of the Global Economy model focusing on agriculture and land use (ADAGE-ALU), is used to examine how the global economy, especially energy, agriculture and land use, responds when facing these challenges.

Though there are many studies analyzing these issues individually or combined to some extent, they are generally subject to limitations. Wise et al. (2012) use an integrated assessment modeling system, MiniCAM, and find that when all carbon is valued, land with unmanaged ecosystems and managed forestland provide increased carbon sequestration, resulting in rising crop prices and reduction of cropland area. The dominant use of bioenergy in their scenarios is bioelectricity with CO2 capture and storage (CCS). However, their work ignores N2O and CH4

emissions from agricultural production and does not capture the impact from changing climate. Reilly et al. (2012) use a dynamically linked modeling system, EPPA-TEM, to explore the role of land in global climate mitigation. This study does not model first generation biofuels and ignores their impact on agricultural and food prices. The findings of this study differs from Wise et al. (2012) in that bioenergy is mainly biofuels rather than bioelectricity.

The version of ADAGE used for this study is a recursive dynamic, multi-region and multi-sector CGE model that focuses on agriculture, bioenergy and land use change (ADAGE-ALU). The model projects the global economy, energy use, agricultural activity, and biofuels production and land use from 2010 to 2050 at 5-year time steps. Agriculture consists of eight crop categories, one livestock sector, and one forestry sector. Biofuel sectors include seven first generation biofuels and three second generation biofuels (Beach et al., 2011). The details included on crops and biofuels enable the first and second generation biofuels to be modeled separately, where the first generation biofuels use key crops or oil seeds as inputs, so land are is indirectly used through the production of crops. For the second generation biofuels, biomass production and biofuels transformation are merged into a single sector, accounting for input uses at all stages in a single production function – thus land enters the production function directly. Land required by agriculture and second generation bioenergy is stratified into five land classes (cropland, pastureland, managed forest land, natural forestland and grassland) and can be converted from one type to another, depending on the prices of inputs and outputs and changing land productivities. A nested constant elasticity of substitution (CES) function framework is used to model land-use change, covering both the cost of land conversion and willingness to convert land in the long run. ADAGE-ALU has been widely applied for food, energy and climate change related studies, including evaluation of US Renewable Fuel Standards (Cai et al, 2013; Birur et

al, 2011) and assessment of climate change impacts on agricultural production (Beach and Cai, 2013), implications of oil prices for global biofuels and GHG mitigation (Cai, Beach, and Zhang, 2014).

2. Model

Our point of departure is the Applied Dynamic Analysis of Global Economy (ADAGE) model described in Ross (2009). ADAGE is a forward looking, intertemporally-optimizing computable general equilibrium (CGE) model. It can be used to simulate global and regional economy, trade, and greenhouse gas emission. Economic data in ADAGE come from the GTAP and IMPLAN databases. Energy data and various growth forecasts come from the International Energy Agency and Energy Information Administration of the U.S. Department of Energy. Emissions estimates and associated abatement costs for six types of greenhouse gases (GHG) are also included in the model. ADAGE is composed of three modules "International, "US Regional" and "Single Country". Each module relies on different data sources and has a different geographic scope, but all have the same theoretical structure. This allows the model to estimate global results as well as detailed regional and state-level results that incorporate international impacts of policies. Adage is widely used to examine economic, energy, environmental, and trade policies at the international, national, U.S. regional, and U.S. state levels and estimate how an economy will respond over time to these policy announcements (for example, Waxman-Markey climate change Bill and the American Clean Energy and Security Act of 2009).

ADAGE-Biofuel is built upon on the ADAGE "International" module by introducing more details on crops, biofuels and land-use changes components. ADAGE-Biofuel is a recursive dynamic, multi-region and multi-sector CGE model. The base year is 2010. It projects global economy, energy use, agriculture activity, biofuel production and land use from 2010 to 2050 at

5-year time steps. Economic development from 2010 is calibrated to the actual output. Economic growth would match the projection of GDP growth trend from International Energy Agency (IEO). Production and consumption sectors in ADAGE-Biofuel are represented by nested Constant Elasticity of Substitution (CES) functions including special cases such as the Cobb-Douglas and Leontief. The model is written in the GAMS software system and solved using the MPSGE modeling language (Rutherford, 1995).

2.1 Data

2.1.1 Baseline Data

The major underlying database for ADAGE-Biofuel, the Global Trade Analysis Project (GTAP) database version 7.1 (Narayanan and Walmsley, Ed., 2008), is updated from 2004 to the baseline year 2010 using secondary data from International Energy Agency, Food and Agricultural Organization (Beach et al, 2012). We aggregate the data into 8 regions and 36 sectors[1] (see Table 1 and Table 2) where agriculture consists of eight crop categories, one livestock and one forestry sector. Biofuel sectors include seven first generation biofuels and three second generation biofuels. The sectors are aggregated such that we could focus on the linkages among energy commodities, biofuels, feedstock crops, by-products and other important related sectors, and biofuels producing countries are emphasized in the regional aggregation.

Table 1. Regions in ADAGE-Biofuel

Regions	Definition
USA	United States
BRA	Brazil
CHN	China
EUR	Europe Union 27
XLM	Rest of South America
XAS	Rest of Asia

[1] The region and sector specification in ADAGE-Biofuel is flexible. Another version of ADAGE-Biofuel has 25 region and 42 sectors.

AFR	Africa
ROW	Rest of World

Since the GTAP data base does not explicitly include biofuel-related data, we used the Splitcom, software developed by Horridge (2005), to break out the existing GTAP sectors. For example, corn-ethanol is split from food sector (ofd) and soy-biodiesel from the vegetable oils and fats (vol) sector and the sugarcane based ethanol from chemicals sector. The by-products such as distillers dried grains with solubles (DDGS) are introduced such that the total corn-ethanol industry jointly produces both corn-ethanol (ceth) and DDGS (ddgs). In order to split out a new sector in general, we used the information on trade shares, consumption shares, cost share and own use shares, in the existing aggregated sector, based on secondary data sources from Food and Agricultural Organization (FAO), IEA, U.S. Department of Agriculture, Energy Information Administration (EIA), U.S. Department of Energy, etc.

Table 2 Sectors in ADAGE-BIOFUEL

Sectors	Definition	Sectors	Definition
Energy		***Industry***	
Col	Coal	Eim	Energy-intensive manufacturing
Cru	Crude Oil Extraction	Man	Other Manufacturing
Ele	Electric generation	Srv	Services
Gas	Natural Gas	Trn	Transportation
Oil	Refined Petroleum	Vmt	Household transportation
Agriculture		House	Housing
Wht	Wheat	***Biofuels***	
Corn	Corn	Ceth	Corn Ethanol
Gron	Rest of Cereal Grains	Weth	Wheat Ethanol
Soyb	Soybean	Scet	Sugarcane Ethanol
Osdn	Rest of Oilseeds	Sbet	Sugarbeet Ethanol
Srcn	Sugarcane	Sybd	Soy Biodiesel
Srbt	Sugarbeet	Rpbd	Rape-Mustard Biodiesel
Ocr	Crops nec	Plbd	Palm-Kernel Biodiesel

Liv	Livestock	Swge	Advanced cellulosic ethanol from switchgrass
Frs	Forestry	Celd	Advanced cellulosic biodiesel
Food		Msce	Advanced cellulosic ethanol from miscanthus
Mea	Meat	***Byproducts***	
Vol	Vegetable Oils	Ddgs	Distillers grains with solubles (DDGs)
Ofd	Other foods products	Omel	Vegetable Oil Meal

2.1.2 Dynamic data

Economic growth in the future periods is driven by capital savings and investments, technological improvements in energy efficiency, growth in the effective labor supply from population growth and changes in labor productivity and change of natural resources stocks such as energy and land.

The key data include population from World Development Indicators, GDP growth, are based on IEA world energy outlook projections. Energy consumption, energy price are also downloaded from there to compare our results and their projections. The rest data are either directly from EPPA, or following the formulation in EPPA (Reilly et al (2012)).

2.2 Model Structure

The general structure of the ADAGE model is discussed in greater detail in Ross (2009). The ADAGE model follows the classical Arrow-Debreu general equilibrium framework covering all aspects of the economy, including production, consumption, trade, investment, etc. Production and household consumption are represented by a nested constant elasticity of substitution framework and discussed in Beach et al (2010). A representative household in each region would maximize its utility subject to budget constraints based on endowments of factors of production (labor, capital, natural resources, and land inputs to agricultural production). Income from sales of factors is allocated to purchases of consumption goods and to investment. All goods, including

total energy consumption, are combined using a CES structure to form aggregate consumption goods. This composite good is then combined with leisure time to produce household utility. The elasticity of substitution between consumption goods and leisure, is controlled by labor supply elasticities and indicates how willing households are to trade off leisure for consumption. Keep in mind that the households are allowed to substitute different types of biofuels to refined petroleum, used in the personal vehicle transportation.

For various sectors in the economy, the general nesting structure of production activities and associated elasticities in ADAGE-Biofuel have been adapted from the EPPA model. Although EPPA has only one crop sector, ADAGE-Biofuel models 8 types of crops, which are produced by utilizing land, labor, capital, energy, and material inputs, with different elasticity of substitution. The livestock production structure in the ADAGE-BIO is separated for ruminants and non-ruminants to reflect differentiated use of biofuel by-products by different animals. At the bottom of the CES production structure, the DDGS is combined with other feed grains, and vegetable-oil meal is combined with oilseeds, and the two composites are allowed to substitute with the processed feed in the livestock production nest.

2.2.1 Modeling biofuel production

Currently cellulosic biofuels is not available in the market. We introduced the cellulosic feedstock (corn-stover, switchgrass, and miscanthus) based production technologies for cellulosic ethanol and cellulosic diesel in the model, such that the cellulosic biofuels could be produced in the post-2010 scenarios. The parameters for the second generation biofuels are taken from EPPA.

The first and second generations of biofuels in the ADAGE-BIO model are produced in a Leontief production structure, where the input shares are fixed over time (see figure 4). The feedstock crops enter the top level of the CES production nest in fixed proportions, along with the

material inputs and capital-labor composite. The capital and labor are combined in value added composite following the Cobb-Douglas production structure. However, the second generation biofuels are currently not available. They can endogenously enter the market when they become cost competitive with rising energy price.

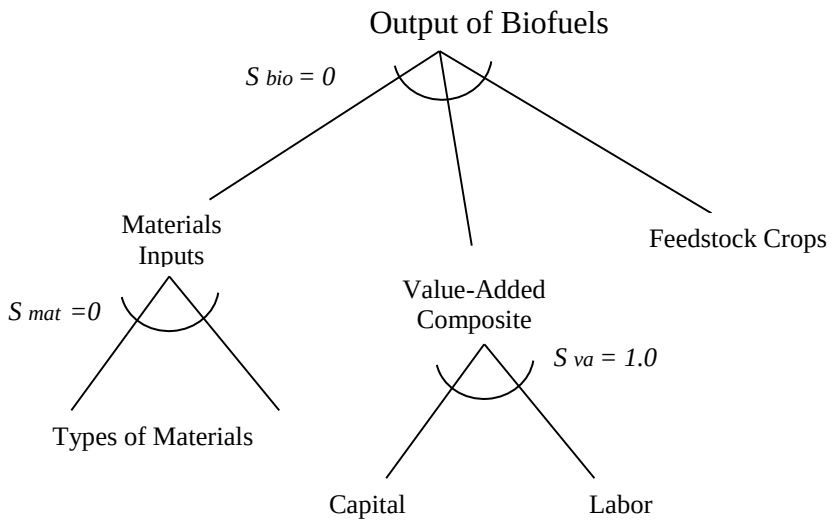

Figure 4. Biofuels production in ADAGE-BIO

2.2.2 Modeling land use change

The land use change in Beach et al (2010) is specified as a nested constant elasticity of Transformation (CET) function where the land is first allocated across three cover types (cropland, pastureland, and forestland) and in the second tier cropland is allocated across 8 alternate crops. After shift in cropping patter within in the cropland, additional demand for land is met by the pasture and forest covers. A land supply elasticity of each type is implied by the elasticity of substitution and implicitly reflects some underlying variation in suitability of each land type for different uses and the cost to or willingness of owners to switch land to another use. The CET approach can be useful for short term analysis. This approach has been criticized as share preserving which assures that radical changes in land use does not occur, making longer

term projections unrealistic. Meanwhile, this approach does not explicitly account for conversion costs, nor address the value of the stock of timber when natural forest land is converted to managed forest land. We also find out total land over time in a region couldn't remain constant, thus fails to maintain the physical account consistency.

Following Gurgel et al (2008), we adopted a CES approach for land use transformation. Land is separated into five types: cropland, pasture land, managed forestry land, natural forest and natural grassland. Cropland could be used to grow various crops and second generation biofuels. Pasture land and managed forest land are exclusively used by livestock sector and forestry sector respectively. Natural grassland and natural forest land could provide no-use value.

Land could be converted from one type to another type. To integrate land use change into the CGE framework, two key requirements have to be retained: (1) consistency between the physical land accounting and the economic accounting in the general equilibrium setting; (2) introduced land use data needs to be consistent with observations as recorded in the base year, so the base year would be still in the equilibrium as observed. To retain consistency between physical land accounting and economic accounting, we assume that one hectare of land of one type is converted to 1 hectare of another type, and through conversion it takes on the productivity level and land rent for that type for that region. It is in that sense that another type of land is "produced." To achieve the second requirements, the marginal conversion cost of land from one type to another should be equal to the difference in value of these two types. A fixed factor and the elasticity between it and other inputs are introduced into the top level of the land transformation function, representing the long-term response of land use change (see figure 5). The lower level would follow the same structure of agriculture production function. This structure is quite simple for pasture land and forest land as they are exclusively used by livestock

sector and forestry sector respectively. It would be more complicated for cropland. As cropland is used for eight types of crops and cellulosic biofuels (once cellulosic biofuels become cost competitive), the production function for cropland is obtained by taking the share of these aggregated eight crops. When natural forest land is converted to forest land, timber is also produced in addition to the "produced" managed forest land. On the other hand, when managed land can be abandoned and converted to natural land, no cost is associated with the conversion.

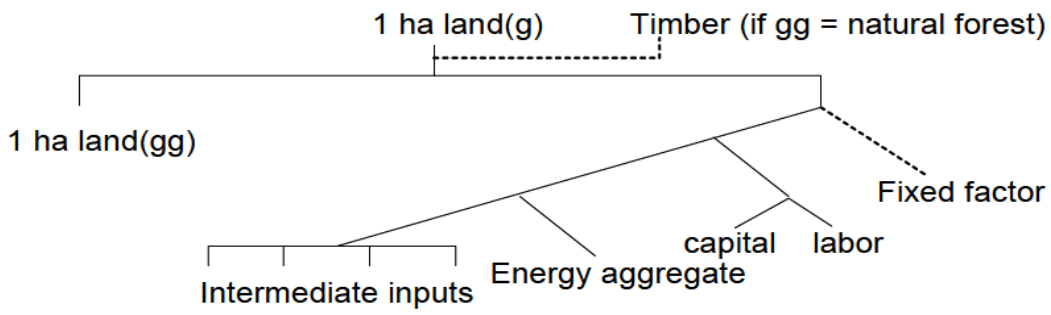

Figure 5. Land use change function (g is one type of land and gg is another type of land)

2.2.3 Modeling GHG Emissions

As ADAGE-Biofuels has a disaggregated agricultural sector with reasonably fine resolution and covers multiple renewable fuels pathways, including cellulosic biofuels, we consider this model in a good position to capture the long-term role of cellulosic biofuels and uncover the benefit/cost of both the first and second generation biofuels. Combining data from National Greenhouse Gas Emissions Data from U.S. Environmental Protection Agency (EPA) and National Greenhouse Gas Inventories from IPCC, we introduce sectorial GHG emissions as well as emissions from land-use change into the model –thus we are able to examine the implications of biofuels policies on land-use emissions.

For this study, six types of GHG (CO2, CH4, N2O, SF6, PHC, and HFC) and their emissions from all sources are introduced into the model using data from various sources. Fossil fuel combustion related GHG emissions enter into the energy consumption block, while emissions not related to fossil fuels combustion are modeled as an input in the nested production structure with an elasticity of substitution representing the emission abatement. When GHG emissions are priced equally for all sources, emissions could be abated through substituting other inputs. Carbon emission or sequestration from land is introduced to the land conversion function. Taking consideration of the dynamic nature of forest carbon accounting in a recursive dynamic CGE model, the annualized value of carbon emission or sequestration for a hectare of land conversion is:

$$V_t = (r + \delta)P_t S_T$$

where V is the annualized return from land conversion at year t, consisting of the sum of discount rate r and the annualized rate δ (where δ=1/T and T is the number of years to reach a new equilibrium carbon stock level after land conversion) multiplied by the carbon price Pt and the difference of carbon stock from land conversion, labeled here as ST. When land is directly diverted for second generation bioenergy production, the difference between net land emissions associated with biofuel production and emission from energy-equivalent gasoline is accounted in the biofuel investment decision within ADAGE-ALU.

2.2.4 Implementing Scenarios

In this study, five scenarios are designed to explore the tradeoffs when facing energy, food and climate challenges: 1) A business-as-usual scenario (BAU) where regional GDP projections are based on the reference case in the International Energy Outlook 2013; 2) A climate change scenario (CC) where crop and livestock productivity are affected by climate

change; 3) A biofuel scenario (BIO) where a carbon tax is applied to all GHG emissions except emissions from land use change, stimulating the expansion of global biofuel production; 4) A reducing emissions from deforestation and forest degradation (REDD)-like scenario where a carbon tax is applied to all GHG emissions, including emissions from land-use change, giving incentives to afforestation or reforestation; and 5) A combined scenario (CC+REDD) where CC and REDD are implemented together.

3. Results and Conclusion

3.1 Global Ag and Food Production

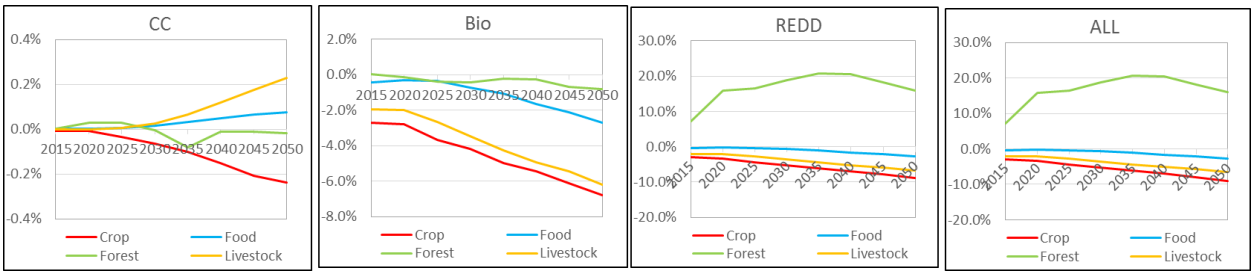

Figure 1. Percentage change of global ag and food production by scenarios, versus BAU case

3.2 Global Ag and Food Consumption

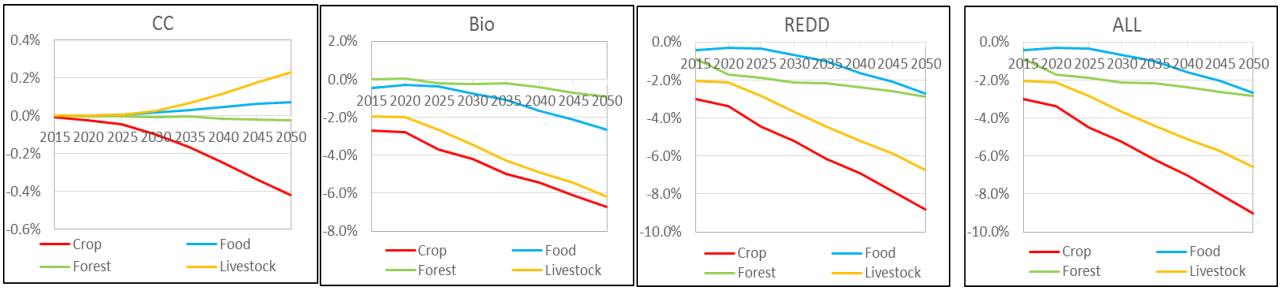

Figure 2. Percentage change of global ag and food consumption by scenarios, versus BAU case

3.3 Global Energy Consumption

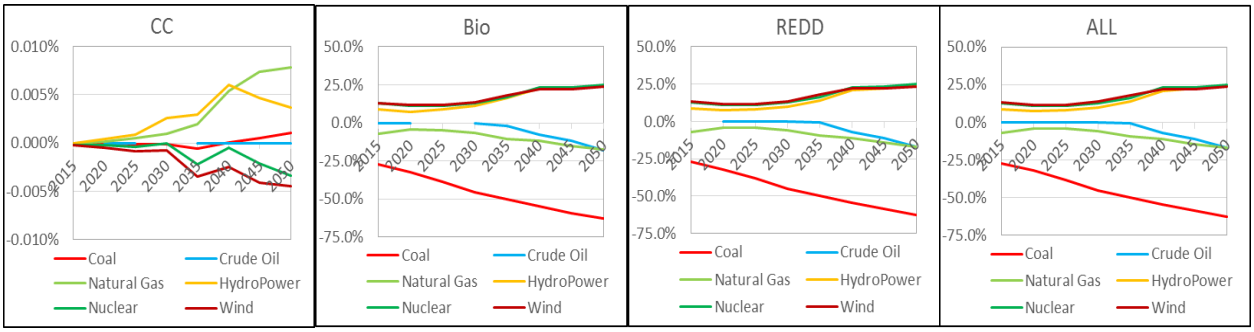

Figure 3. Percentage change of global energy consumption by scenarios, versus BAU case

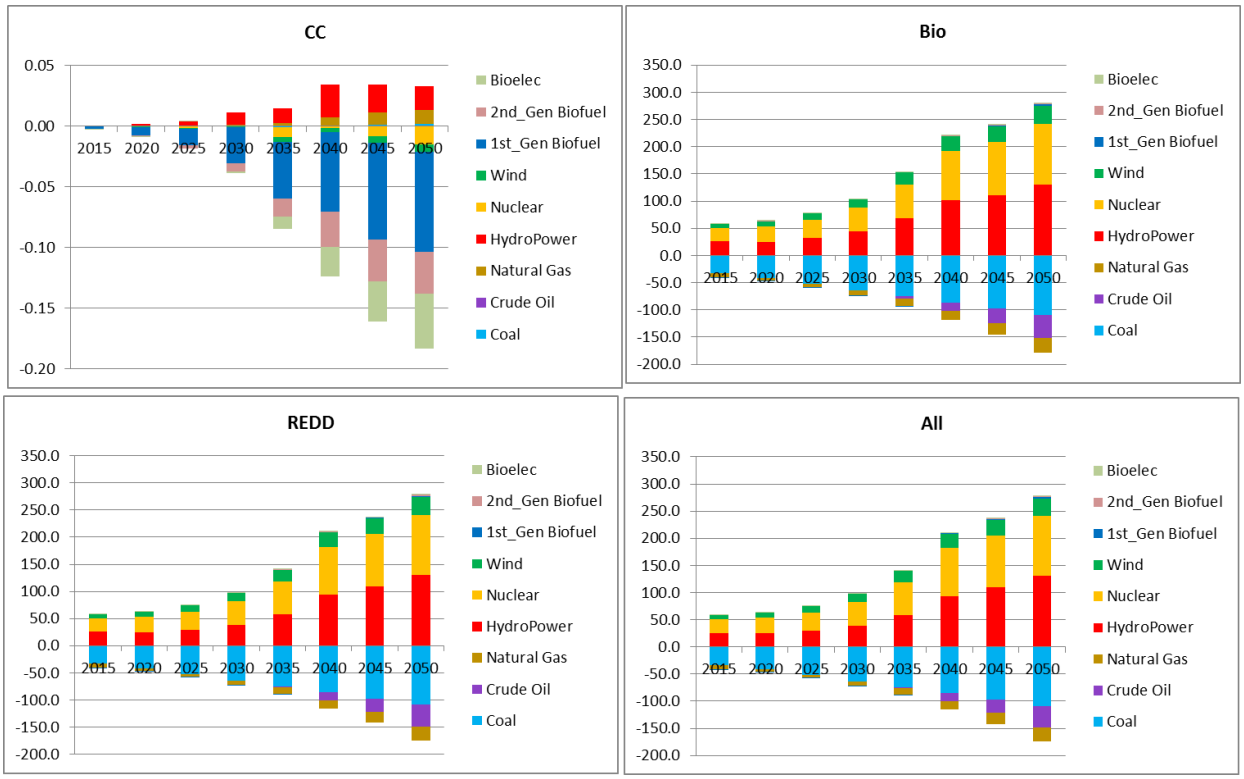

Figure 4. Change of global energy consumption by scenarios, versus BAU case

3.4 Global Average Price for Agriculture

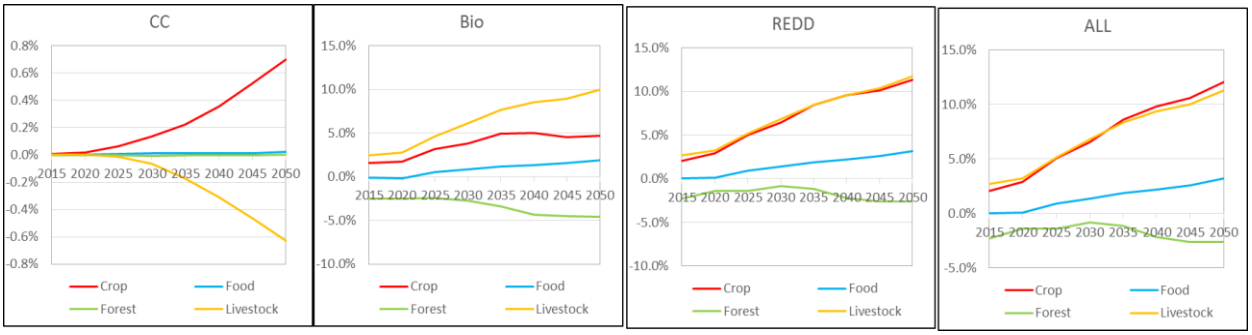

Figure 5. Percentage change of global ag price by scenarios, versus BAU case

3.5 Global Average Price for Energy

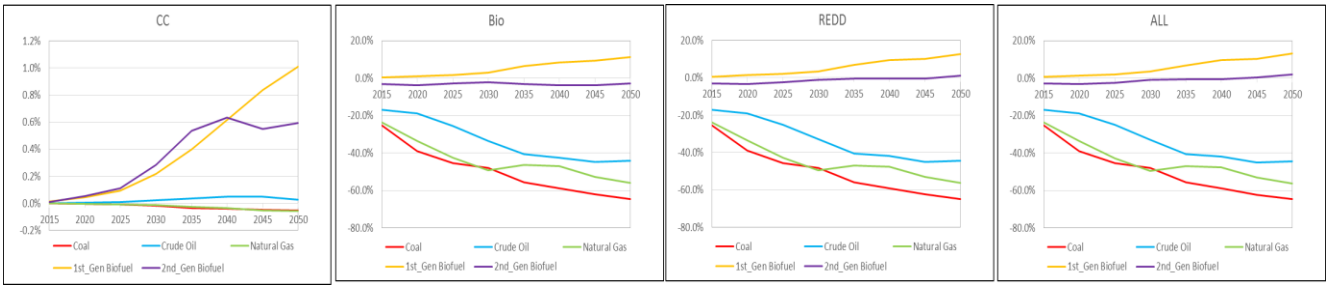

Figure 6. Percentage change of global energy price by scenarios, versus BAU case

3.6 Global Land Cover

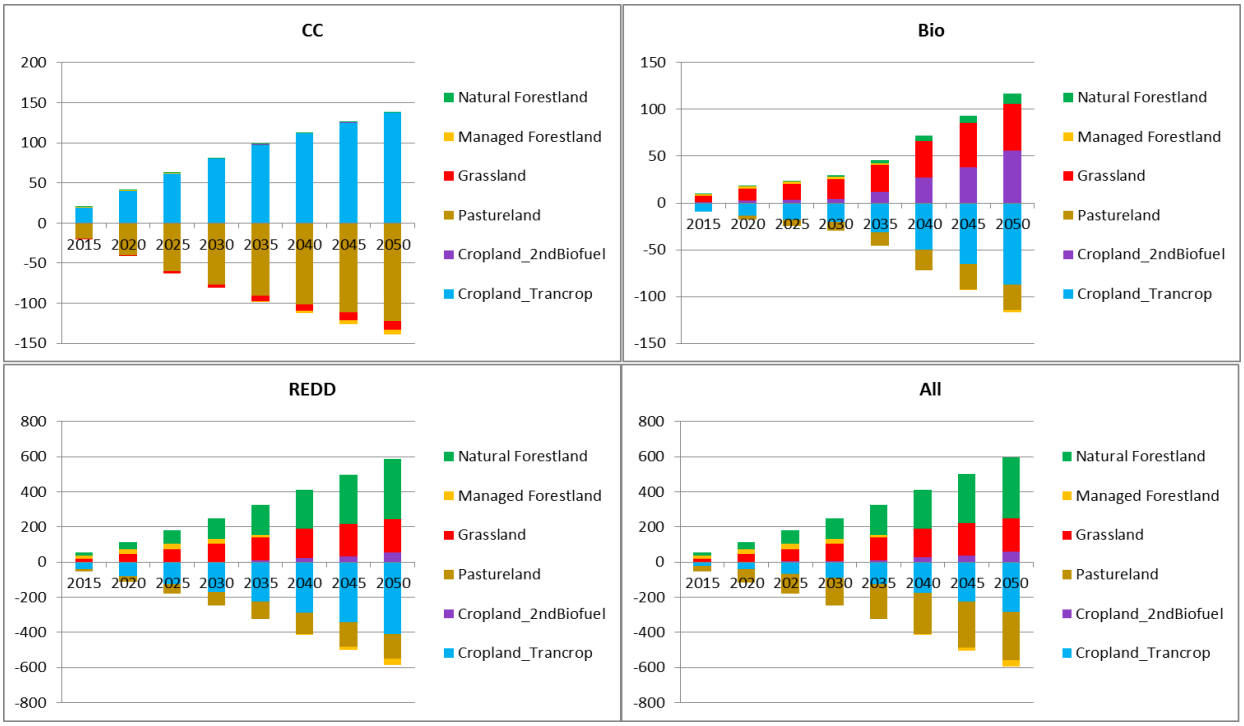

Figure 7. Change of global land cover by scenarios, versus BAU case

3.7 Global GHG Emissions

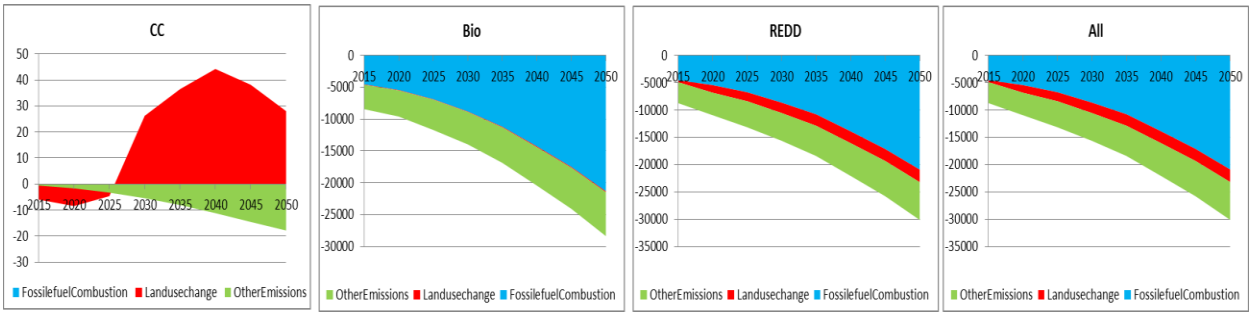

Figure 8. Change of global ghg emissions by scenarios, versus BAU case

Our preliminary results indicate that despite continued increases in land productivity and energy efficiency in future decades, the effects of population and economic growth would dominate, leading to global increases in agricultural production, but also rising food and energy prices as well as continually growing GHG emissions in the BAU scenario. Comparing the

climate change scenario with the BAU scenario, there are substantial reductions in global crop production and significant further increases in food prices, but little change in fossil fuel and biofuel production and energy prices, and only mild increases in CO2 emissions due to land-use changes. Relative to the BAU case, the implementation of a carbon tax on emissions other than those from land use change leads to the expansion of global biofuel production and a shift in the mix of crops produced towards those used as biofuels feedstocks, raises food prices, and reduces oil consumption and price slightly. Meanwhile, GHG emissions are slightly reduced as a result of lower oil consumption. In the REDD scenario, some cropland is afforested to store carbon, leading to a moderate rise in food and energy prices and significant GHG emission reductions. When climate change, REDD scenarios are implemented together, we see even higher reductions in global crop production and larger food price increases, along with greater reduction in GHG emissions compared with the CC scenario.

From this study, we are able to examine how the global economy responds when facing multiple pressures from rising food and energy demand under climate change in a more comprehensive and disaggregated manner than many previous studies. When designing policies, individual countries should take into consideration the overall costs and benefits associated with domestic energy, food security, and climate mitigation policy as well as the interactions of domestic policy with international policies.