[*Preliminary Draft – Do Not Cite or Quote*]

A DYNAMIC GENERAL EQUILIBRIUM ANALYSIS OF U.S. BIOFUELS PRODUCTION

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Selected Paper prepared for presentation at the Agricultural & Applied Economics Association's 2011 AAEA & NAREA Joint Annual Meeting, Pittsburgh, Pennsylvania, July 24-26, 2011.

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Abstract

With the rising global interest in energy security and climate change mitigation, biofuels have gained the prominent attention of researchers and policy makers. The U.S. has emerged as the leading producer of biofuels and is aiming for achieving a target of 36 billion gallons of renewable fuels by 2022 under its updated renewable fuels standard (RFS2) policy. In this paper, we study the longer-term global implications of large-scale renewable fuels production in the U.S. We utilize the GTAP v7.1 data base and introduce a detailed breakdown of agricultural crops, first and second generation biofuels and by-products. We update this fully disaggregated data base to reflect the 2010 global economy, based on secondary data for the sectors and regions included. We adapt the Applied Dynamic Analysis of Global Economy (ADAGE) model developed by Ross (2009) into a recursive dynamic framework and introduce agriculture, biofuels, and land use linkages. We construct a dynamic baseline from 2010 through 2050 in five-year time steps. The dynamics in the model comes from growth in GDP, population, capital accumulation, labor productivity, growth in natural resource stocks, and technological changes in the energy intensive and agricultural sectors. We implement a representative RFS2 policy scenario in the U.S for 2025, using two alternative approaches: (i) RFS permits approach – which assumes biofuels and petroleum fuels are perfect substitutes after adjusting for energy content, and (ii) Target share of biofuels in transportation fuels approach – which treats biofuels and petroleum fuels as imperfect substitutes. Both approaches offer insights regarding potential policy impacts, particularly on the international market and indirect land use change. Because the share approach keeps the biofuels share fixed in the regions outside the U.S., it does not result in dramatic changes in the rest of the world. In the permits approach, however, the regions without a specific policy requiring a given level of biofuels tend to reduce biofuels consumption. This is a result of the reduction in relative price of petroleum products as U.S. policy increases demand for biofuels and reduces global demand for petroleum, making renewable fuels less cost-competitive in the rest of the world.

Key Words: ADAGE, Biofuels, Computable General Equilibrium, Recursive Dynamic.

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1. Introduction

Biofuels are gaining prominence in many countries around the world, particularly due to growing concerns on energy security and climate change mitigation. As the International Energy Agency (IEA) reports, about 45 countries produced biofuels for transportation in 2008, amounting to more than 23 billion gallons. A roadmap for biofuels developed by IEA (2011) finds that biofuels have the potential to increase their contribution from their current global share of 2% to about 27% of total transportation liquids by 2050 while meeting sustainability guidelines, given that appropriate technology deployment and policy incentives are in place. Nonetheless, meeting the rising demand for transportation fuels through sustainable means remains a challenge for the major energy consuming countries. The U.S. currently consumes about 25% of world oil production, about 60% of which comes from imports (EIA, 2010). Biofuels such as ethanol and biodiesel are currently produced primarily from agricultural sources in the U.S. and have experienced an unprecedented growth in the previous decade. This growth is mainly driven by several federal and state policy measures such as the blenders credit, production tax credit, import tariff, and the renewable fuel standard (RFS) as expanded by the Energy Independence and Security Act (EISA) of 2007, which increased the renewable fuels volume requirement and added minimum net GHG reduction levels for qualification as conventional or advanced biofuels (U.S. EPA, 2010). With these policies in place, the U.S. has emerged as the leading producer of biofuels with 12.2 billion gallons (bg) of corn-ethanol and 893 million gallons (mg) of oilseed-based biodiesel in 2010. However, the total consumption of ethanol in the U.S. in 2009 is still only 5.3% on a gasoline-equivalent basis and that of biodiesel constituted 1.2% on a diesel-equivalent basis (Schnepf, 2010).

The updated requirements are commonly referred to as RFS2 and mandate the use of 36 billion gallons of total renewable fuels per year by 2022. As seen from Figure 1, the RFS2 volume requirement includes up to 15 bg of ethanol from traditional starch-based sources (almost all corn-based in the U.S.) that meet the GHG reduction standards to be classified as a renewable fuel but not an advanced biofuels. The remaining 21 bg of other renewable fuels are derived om such as advanced biofuels including cellulosic biofuels (16 bg), biomass based biodiesel (1 bg), and 4 bg of other unspecified biofuels (mostly imported sugarcane ethanol). Apart from the volume mandates, the EISA also specified the thresholds on lifecycle greenhouse gas (GHG) emissions on the qualifying biofuels such as 20% for corn-ethanol, 60% for cellulosic biofuels, 50% each for biodiesel and other advanced biofuels. Since most of these fuels are sourced from agriculture and forest resources, large scale production of biofuels results in far-reaching intended and unintended consequences on the economy and environment. In this study, we examine the longer-term global implications of complete execution of the U.S. RFS2 policy.

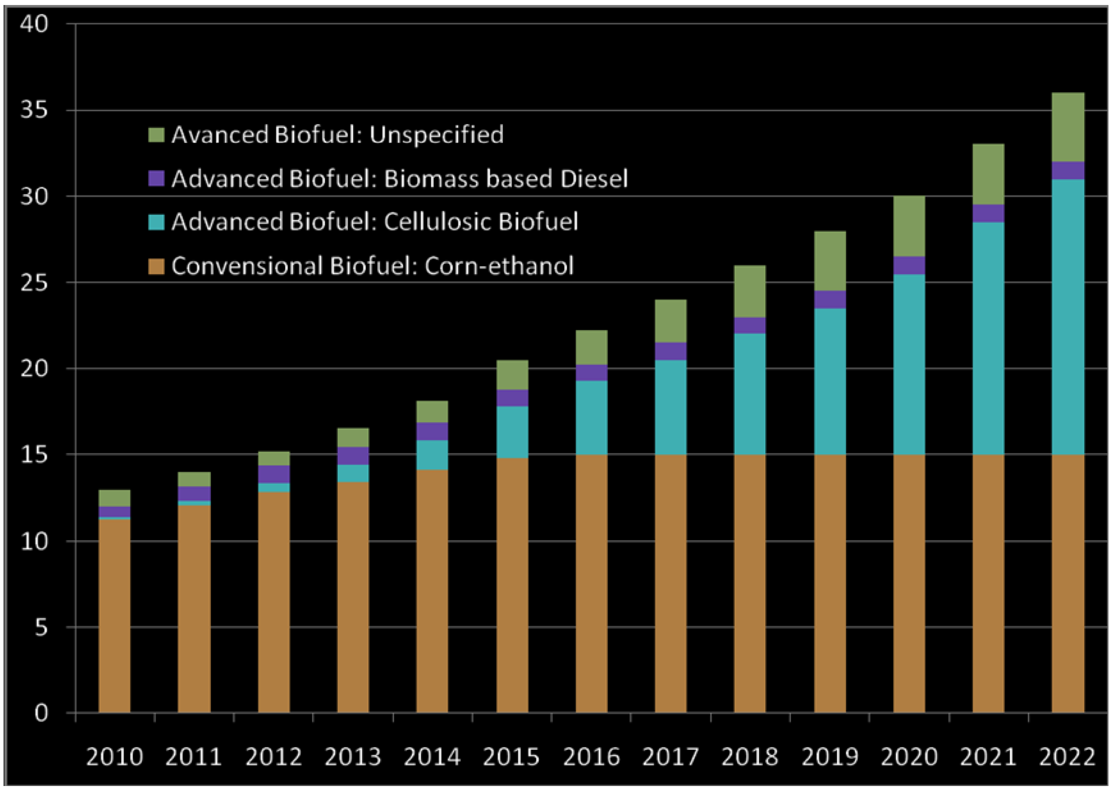

Figure 1. RFS2 volume requirements (billion gallons).
Source: USEPA (2010).

Though several studies in the recent past have analyzed economy-wide implications of biofuels, they suffer from major caveats of being a static, general or partial equilibrium, or being specific to a single region. For instance, Birur et al. (2008), Hertel et al. (2010), and Taheripour et al. (2010) have used a comparative-static version of Global Trade Analysis Project (GTAP) model for analyzing global impacts of biofuels, byproducts, and land use change at the Agro-Ecological Zonal (AEZ) level. Though this framework suits well for analyzing short-term implications, for analyzing the longer-term implications, it is important to account for time varying macro-economic and technological change components, with greater details on the types of biofuels and feedstock crops.

A few studies on biofuels policies have been carried out by adapting the MIT Emission Prediction and Policy Analysis (EPPA) model, a recursive dynamic, multi-sector, multi-region, general equilibrium model. The EPPA model adopts the GTAP data base to account for the input-output structure of the regional economies for the year 1997 and also includes additional information on GHGs emission and disaggregated energy supply. Gurgel et al. (2008) disaggregate the agricultural sector into crops, livestock, and forestry subsectors and allow for conversion of land across five land types: cropland, pastureland, harvested forestland, natural grassland, and natural forestland. A key feature of this study is the cost of conversion approach used in land use modeling, which keeps track of land conversion costs and value of timber stock resulting from conversion. Gitiaux et al. (2009) study the effect of biofuels mandates on the European vehicle feet, by adapting the MIT EPPA model. They introduce seven types of first generation biofuels technologies in the model and also account for CO_2 emissions resulting from growing feedstock crops as well as from biofuels conversion. Those authors treat the diesel and gasoline vehicles explicitly, accounting for asymmetry in the European fuel tax system as well as the differences in fuel efficiency. Though this study examines the interaction of biofuel mandates, fuel tax, and tariff policies over the long-term (2030), it completely ignores the emerging cellulosic biofuels which potentially have significant impact on land use and CO_2 emissions.

Al-Riffai et al. (2010) analyzed the impact of EU and US biofuels policies, by adapting the Modeling International Relationships in Applied General Equilibrium (MIRAGE) model and introducing the first generation biofuels into the GTAP version-7 data base. Those authors augment the MIRAGE model with modules on energy and biofuels interaction, feedstocks and co-products of biofuels, and AEZ level CET land supply structure similar to that of Birur et al. (2008). They examine the EU renewable energy target of 10% of transportation fuels by 2020, from the 5.6% share in the base year 2008. The study reveals that EU mandates requires considerable imports of ethanol from Brazil, with a global next balance of direct and indirect emissions of 13Mt CO_2 savings over 20 years horizon. This study did not consider the cellulosic biofuels in their analysis.

The purpose of this study to develop a comprehensive global model in a general equilibrium framework, with detailed agriculture, energy, and first and second generation biofuels sectors, allowing for long term macro-economic changes, technological development, and consumption changes in energy and food sectors. The following sections describe the study approach, description of the data base with biofuels and feedstock crops, construction of baseline to 2050, structure of the ADAGE model, experimental design to implement RFS2 policy scenarios, discussion of results comparing share and permits approaches, and conclusions.

2. Study Approach

In this study we adapt Applied Dynamic Analysis of Global Economy (ADAGE) model developed by Ross (2009) and introduce agriculture and biofuels linkages. The ADAGE model is a forward looking, intertemporally-optimizing computable general equilibrium (CGE) model with perfect foresight behavior of agents. The model has well developed energy and GHGs modules with a focus on climate policy analyses. Some of the key features include the electricity sector is differentiated by source, the transportation sector is modeled as explicit purchased and personal vehicle transportation. The dynamics in the model comes from capital accumulation, labor productivity, growth in natural resource stocks, and technological changes in the energy intensive sectors. The ADAGE model has alternate versions with distinct international regions and the U.S. regions, which have been used for analyzing the economy-wide impact of various environmental policies, including the recent Waxman-Markey climate change Bill and the American Clean Energy and Security Act of 2009. For the purpose of this study we utilize a recursive dynamic version of the ADAGE model, with baseline projections from 2010 through 2050 and nick name it as ADAGE-BIO. Some of the key inputs to the ADAGE-BIO model are the GTAP data base and baseline construction. The following sections describe incorporation of explicit biofuels related sectors into the GTAP data base and variables included in the baseline.

2.1 Incorporating biofuels into the GTAP data base

For incorporating explicit feedstock crops, biofuels, and by-products into the ADAGE-BIO model, we utilize the GTAP version 7.1 data base (Narayanan and Walmsley, 2008 Ed.), which comprises 57 sectors and 112 global regions pertaining to the global economy in 2004. Since the GTAP data base does not explicitly include some of these biofuels related, we introduce these sectors into the data base by breaking out the existing GTAP sectors. Biofuels are produced mainly from feedstocks such as grain, sugar-crops, oilseeds, and cellulosic feedstock. We introduced four types of ethanol (two starch and two sugar; additional starch-based ethanol pathways and cellulosic feedstocks will enter in future years rather than being incorporated within the base year database) and three types of biodiesel based on the types of feedstock used to produce them in 2004. Since several feedstock crops in the GTAP data base are aggregated, we first split out some of the important crops and then introduced the biofuels and their by-products.

Table 1 below depicts the new and existing sectors that are explicitly represented in the revised GTAP data base (the complete list of sectors is given in Table A2 in Appendix). For instance, corn-ethanol is generated by splitting the food products sector (ofd) which receives the inputs from corn (corn) and soy-biodiesel is generated from the vegetable oils and fats (vol) sector which absorbs inputs from the oil-seed sectors, the sugarcane based ethanol was broken out from chemicals sector (crp) with the input from sugar cane sector, and so on. For any new sector, an existing sector is split based on input-output flow in a particular region. The by-products such as distillers dried grains with solubles (DDGS) are introduced such that the total corn-ethanol industry (Tcet) jointly produces both corn-ethanol (ceth) and DDGS (ddgs). Because the vegetable oil (vol) sector in the GTAP data base also included oil-meal, we modified the data to introduced oil-meal as a joint product of rest of vegetable-oil (volr) sector. These byproducts are allowed to sell as intermediate inputs in the livestock sectors.

Table 1. Explicit biofuels and feedstock sectors split from the existing GTAP sectors.

New Sectors	*Existing sectors used to Split*	*Final Sectors*
Corn	**gro** (cereal grains)	gro = **corn** + gron
Soybean Rapeseed Palm	**osd** (oilseeds) **osd** (oilseeds) **osd** (oilseeds)	osd = **soyb** + **rapm +** **plmk** + osdn
Sugarcane Sugarbeet	**c_b** (sugar cane, beet) **c_b** (sugar cane, beet)	c_b = **srcn** + **srbt**
Corn-Ethanol Wheat-Ethanol	**ofd** (food products nec) **ofd** (food products nec)	ofd = **Tcet** + **weth** + ofdn
Soy-Biodiesel Rape-Biodiesel Palm-Biodiesel	**vol** (vegetable oils) **vol** (vegetable oils) **vol** (vegetable oils)	vol = **sybd** + **rpbd** + **plbd** + voln

Scane-Ethanol Sbeet-Ethanol	**crp** (chemicals) **crp** (chemicals)	crp = **scet** + **sbet** + crpn
DDGS Oil-meal	Joint product of Corn-Ethanol Joint product of vegetable-oil	Tcet = ceth + **ddgs** voln = volr + **omel**

For splitting the existing sectors in the GTAP data base, we used a utility called Splitcom, software developed by Horridge (2005). 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. The trade shares were computed based on data on production, exports and imports across countries. Based on bilateral trade and tariff information on a new sector, the trade margins (surface, water, and air transport) were computed on the basis of margins in the existing sector. The consumption shares indicate how consumption of the new sectors (e.g., biofuels, byproducts, etc.) flows through households, intermediate demands, and government demands. We initially channeled all the biofuels to sell only to households in the data base, but this assumption is relaxed in the ADAGE-BIO model to accommodate blending requirements in the petroleum sector. We obtained the production cost shares, from various secondary sources on cost of cultivation and plant-specific processing cost of biofuels. We also assumed that biofuel sectors have no own use, but the crops sectors were assumed to have a fraction of own use to meet the seed demand. When these shares were computed for each of the new sector, attention was given to keep the social accounting matrix (SAM) balanced as well as to avoid any negative flows across sectors and regions.

Updating the Data Base for 2010: The base year of the ADAGE-BIO model version used in this study is 2010 and it is set up to solve in five-year intervals along the baseline trajectory up to 2050. Therefore, the GTAP data base with biofuels pertaining to 2004 economy was updated using other secondary data on the GTAP sectors and regions for 2010. For example, area, production, yield, and price data for the thirteen GTAP crop categories (Table A2) were obtained by mapping all the 169 crops data from FAO for all the regions from 2001 through 2008. This data was projected to 2010 based on population growth (since the alternate, GDP growth rates were negative for several countries in 2009 and 2010). Similarly, all the 62 categories of livestock data from FAO were mapped to seven GTAP livestock categories and projected the production values for 2010. Production and consumption of energy sectors were also obtained from IEA and EIA energy outlooks to update the data base for 2010.

Since the production of cellulosic biofuels did not exist in 2004, 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.

2.2 Developing a Baseline for 2050

The dynamics in the ADAGE-BIO model comes mainly from: (i) growth in the available effective labor supply from population growth and changes in labor productivity, (ii) capital accumulation through savings and investment, (iii) increases in stocks of natural resources, and (iv) technological change from improvements in manufacturing and energy efficiency. For the biofuels model we further incorporate (v) baseline production of biofuels, and (vi) technological change in the energy intensive, agriculture, and livestock sectors. We compute baseline variables for 2010-2050 period across all the regions, based on data from various secondary sources. The key variables include population from World Development Indicators, GDP growth, energy consumption, price of energy commodities, and electricity generation by source, are based on IEA world energy outlook projections. The baseline projection of biofuels production is based on IEA (2010) and FAPRI (2011) projections. The world production of different types of biofuels projected over 2010-2050 is displayed in Figure A1 in the Appendix. For estimating the agricultural outputs, we utilized the Total Factor Productivity (TFP) estimates by Ludena et al. (2007). A baseline trajectory of per hectare yield of important crops in the U.S. is provided in Figure A2. We assumed that the food consumption trend follows the population growth.

Aggregation of Regions and Sectors: The data base pertaining to 2010 economy is aggregated to permit focus on the sectors and regions of particular interest. For implementing the biofuels RFS2 analyses, we aggregate the data base into 25 regions (Table A1 in Appendix) and 41 economic sectors (Table A2). 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.

2.3 Structure of ADAGE Model

In this section we discussion on the salient features of the biofuels version of the ADAGE-BIO model. 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. Following Gitiaux et al. (2009), we model production of agricultural commodities in a nested constant elasticity of substitution (CES) framework such that the biofuels utilize their respective feedstock crops along with other factor inputs. There are 11 crop sectors produced by utilizing the land, labor, capital, energy, and material inputs, with the varying elasticities of substitution as show in Figure 2. At the top level of the nest, the value added composite is substituted to resource and materials-energy composite with an elasticity of 0.7, allowing for efficiency improvements with use of additional units of capital and labor. The land productivity varies endogenously based on the relative price response across crops which are in turn driven by the elasticity of substitution between land and materials-energy composite.

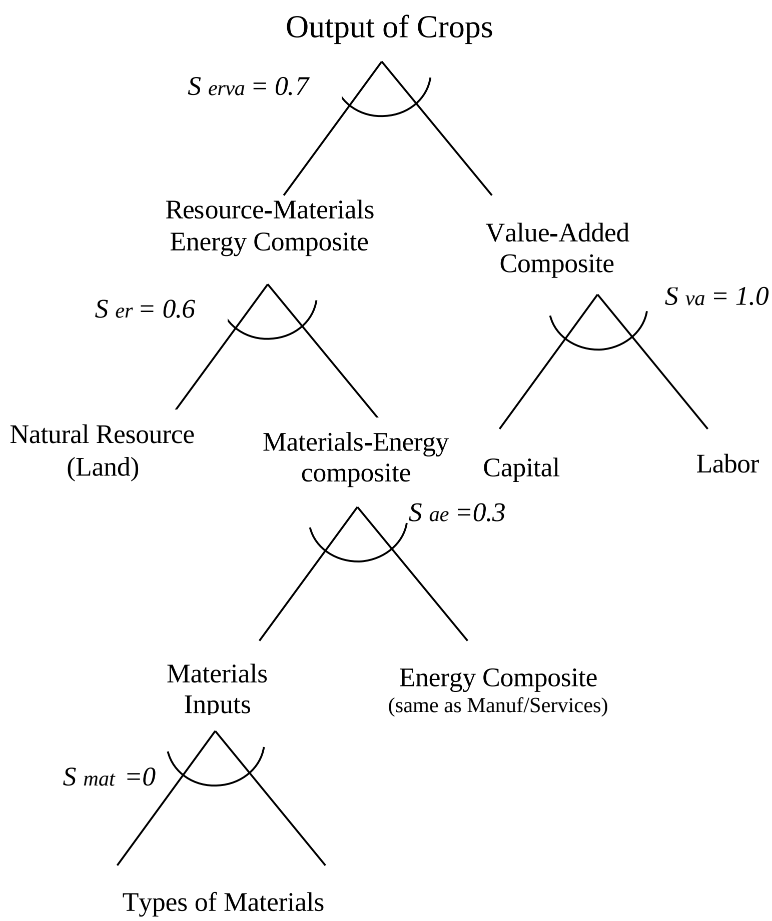

Figure 2. Agricultural production in ADAGE-BIO.

Similar to Birur et al. (2008), the land supply is specified as a nested 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 11 alternate crops. After shift in cropping patter within in the cropland, additional demand for land is met by the pasture and forest covers. Compared to previous studies, the detailed incorporation of explicit crops in this study helps in precisely identifying the change in cropping pattern and distribution[1].

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. 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.

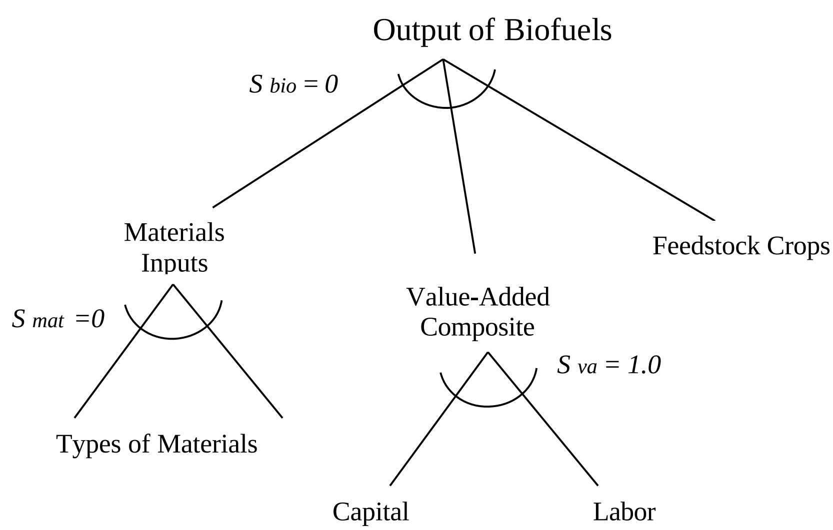

Figure 3. Biofuels production in ADAGE-BIO

[1] Since CET type of land supply function is often criticized as share preserving in nature and hence not appropriate for a long run analysis, our future work also focuses on incorporating cost of land conversion from one type to another, following Gurgel et al. (2008). This approach helps the model to keep track of conversion costs as well the land area converted.

The household consumption structure in the ADAGE-BIO model follows nested CES structure with a representative household in each region maximizing utility in each time period subject to budget constraints. As depicted in Figure 4, at the bottom of the consumption structure, the households are allowed to substitute different types of biofuels to refined petroleum, used in the personal vehicle transportation, with an elasticity of substitution around 2. One of the key features of the ADAGE is, the transportation sector includes explicit purchased and personal vehicle transportation. The transportation and the composite consumption good including energy, goods and services are combined with a Cobb-Douglas specification. In the next stage, the aggregate consumption is combined with leisure to produce household utility or welfare, with an elasticity of 0.95 indicating the relative willingness of the household to substitute between consumption and leisure time. The households own the factors of production employed by the firms and the income from the sale of these factors (land, labor, capital, and natural resources) are allocated for purchase consumption goods to maximize welfare. The imported and domestic commodities in the ADAGE-BIO modules are treated as differentiated Armington goods.

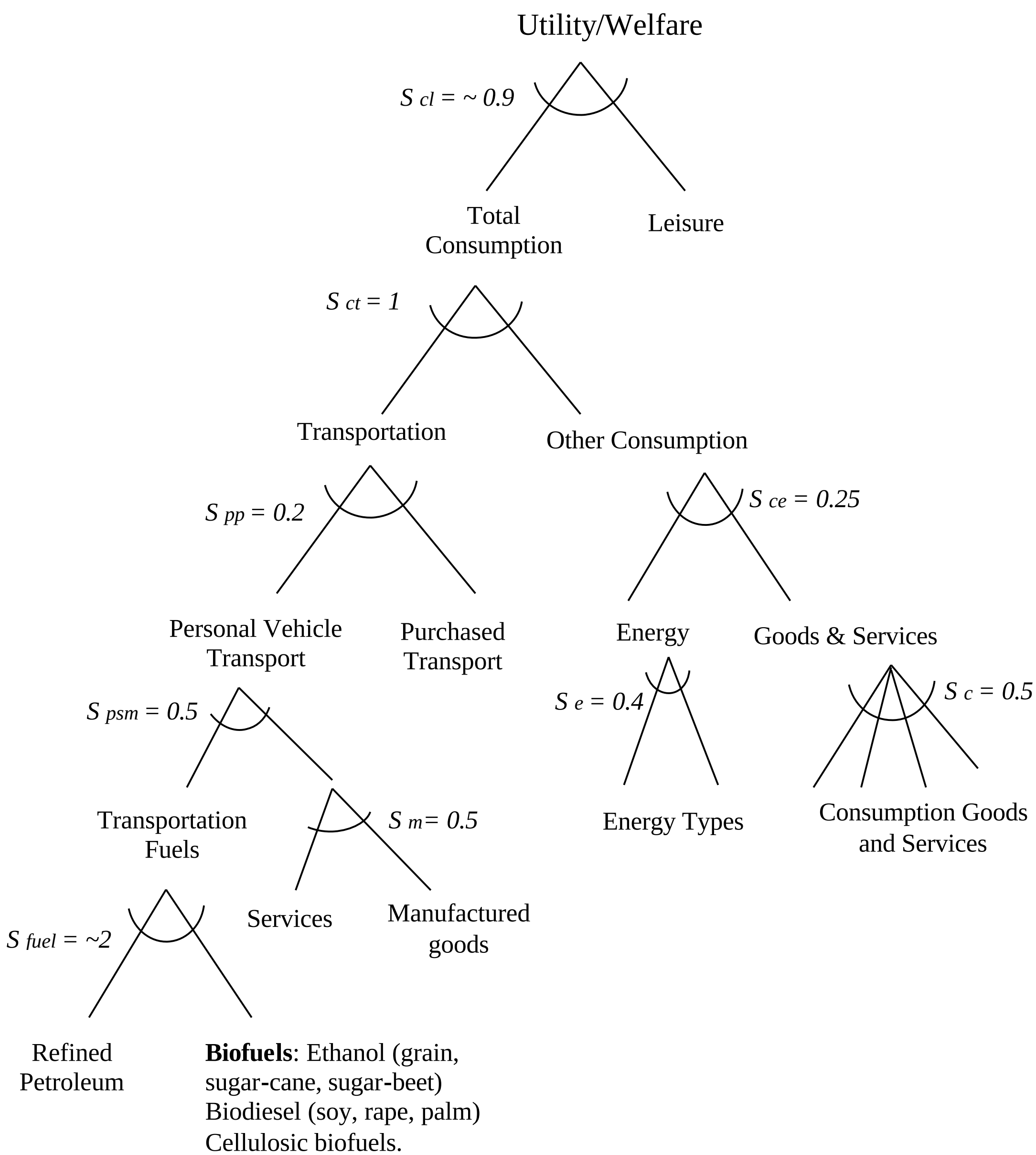

Figure 4. Household consumption structure in ADAGE-BIO

The livestock production structure in the ADAGE-BIO is separated for ruminants and non-ruminants with the intention 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.

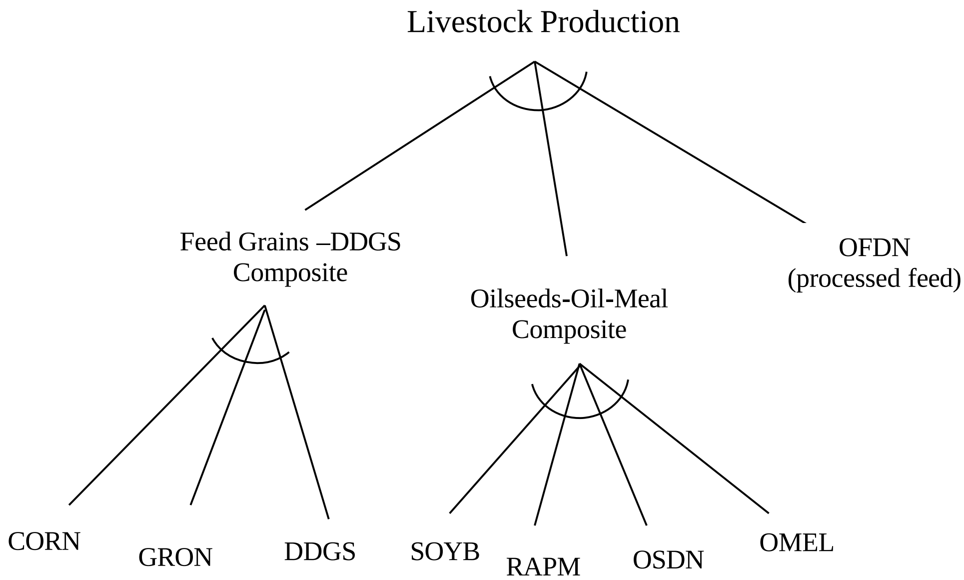

Figure 5. Substitution of feed in livestock production structure in ADAGE-BIO.

3. Experimental Design

As discussed above, the focus of this study is the U.S. RFS2 on biofuels. Starting from the baseline 2010, we implement the 2022 U.S. biofuels mandate which includes 15 bg of corn-ethanol, 13.7 bg of cellulosic biofuels, and 1.47 bg of soy-biodiesel as an advanced biofuel. Any import of biofuels into the U.S. subjected to RFS2 implementation is allowed to adjust depending on the price changes and trade restrictions. We implement this experiment in two alternate cases where the biofuels are treated separately as perfect (permits approach) and imperfect substitutes (share approach) for fossil fuels. The detailed approach is discussed in the following sections.

3.1 RFS2 Permits Approach

The U.S. Environmental Protection Agency administers the RFS by issuing tradable certificates in the form of unique renewable identification numbers (RINs) for tracking each batch of biofuel produced or imported (Schnepf, 2010). The RINs are transferable as the ownership of biofuels change and when biofuels are used for blending, the RINs are used for compliance demonstration, and also for credit trading. We examine the RFS2 policy scenario by implementing the mechanism of issuing permits for biofuels production. We follow Gitiaux et al. (2009) approach, which used a version of the MIT EPPA model to study the impact of European biofuels policy for 2010 and 2020. The study considered only the first generation biofuels, which were introduced into the model based on shares of cost incurred for production. They examined the business-as-usual (bau), mandates, tax-policy, and biofuels import tariff scenarios. For implementing the biofuels policy scenarios, those authors adopted RFS permits approach, which essentially treats biofuels and conventional (petroleum) fuels as perfect substitutes. This approach generates a permit for every unit of biofuels produced by the firms, which are then purchased by the conventional fuel producers for a price in order to meet the targeted share of biofuels in total liquid fuels. They also introduce other types of permits to capture the 10% blending wall and E85 fuel production, using a complement blending process and a fixed coefficient production function, respectively.

3.2 RFS2 Share Approach

This is a straight forward approach, which targets share of biofuels in transportation liquids (used in personal vehicles) based on energy content. Several studies have treated the biofuels as imperfect substitutes to petroleum products (e.g., Birur et al. 2008; Hertel et al. 2010). Unlike the permits approach where the market forces determine the use of a particular biofuel, the shares approach forces the specified level of a particular biofuel in each region.

4. Results (PRELIMINARY)

The RFS policy causes changes in the output quantities and prices of all agricultural commodities, as the use of corn ethanol, switchgrass-based cellulosic ethanol, and soybean biodiesel increase. Mandating the production of these fuels increases the production of their feedstocks and increases the demand for cropland. This increase in demand affects the production of all crops, as well as the prices and quantity of forest and pastureland. The requirement of 13.7 billion gallons of cellulosic ethanol (assumed to come from switchgrass) has a pronounced effect on land use and agricultural output because the feedstock crop does not appear in the baseline and must displace other uses for land. The following sections describe the changes in agricultural and energy markets in the US resulting from the 2025 US RFS policy.

4.1 Output

Output of corn ethanol increases by 3.7 billion gallons, output of soybean biodiesel increases by nearly 1.1 billion gallons, and 13.8 billion gallons of cellulosic ethanol are produced to meet the RFS requirements. These changes in volumes are displayed in Table 2. As land moves into the production of switchgrass, the outputs of all other agricultural products, such as other crops, forestry and livestock products, and other types of biofuels decrease.

Table 2. US motor vehicle fuel use - billion gallons.

	Baseline				Scenario			
	Imports	Exports	Output	Total use	Imports	Exports	Output	Total use
Oil	**27.8**	**11.1**	**113.5**	**130.2**	**25.3**	**10.3**	**89.2**	**104.2**
Ethanol	**0.4**	**0.0**	**11.1**	**11.5**	**0.4**	**0.0**	**14.8**	**15.1**
corn	0.0	0.0	11.0	11.0	0.0	0.0	14.7	14.7
wheat	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
cane	0.4	0.0	0.0	0.4	0.4	0.0	0.0	0.4
beet	0.0	0.0	0.1	0.1	0.0	0.0	0.1	0.1
Biodiesel	**0.2**	**0.6**	**0.7**	**0.4**	**1.1**	**0.6**	**1.0**	**1.4**
soy	0.2	0.6	0.7	0.4	1.1	0.6	1.0	1.4
palm	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cellulosic	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**13.8**
Total bio	**0.6**	**0.6**	**11.8**	**11.8**	**1.5**	**0.6**	**15.7**	**30.4**
Total	**28.3**	**11.7**	**125.4**	**142.0**	**26.8**	**10.9**	**105.0**	**134.6**

Corn and corn ethanol markets: The US RFS policy causes an increase in the amount of corn ethanol used and produced domestically. Corn ethanol use increases from 11 to 14.7 billion gallons, with other types of ethanol making up the rest of the 15 billion gallon requirement. US corn output remains relatively constant (a decrease of less than one percent) and the increase in corn ethanol production is achieved through input substitution, representing a technological change.

4.2 Prices

Energy goods: Within the US, as demand for biofuels increases and the price of land rises, the prices of biofuels increase as well. The price of corn ethanol increases by 1.4%, while the price of soybean biodiesel increases by 15.2%. The increase in energy costs associated with the increase in biofuels use will further reduce demand for conventional transportation fuels by US consumers. The reduction in demand for oil by 25 billion barrels within the US causes the world oil price to fall by 3%. The reduction in oil prices in other regions reduces the prices of crops both by lowering the cost of inputs to production and by reducing the demand for biofuels and the associated feedstock crops. These price changes are reflected in the increase in US imports and decrease in US exports of biofuels. Selected energy price changes are found in Figure 6.

Agricultural goods: Within the US, prices for all agricultural goods rise as land moves into the production of biofuels. The scarcity of land causes changes in the prices of crops of up to 3.5%, and smaller changes in the price of processed foods. Meat prices rise by less than 1% as increasing prices for land and feed are tempered by the increased supply of DDGs available as livestock feed. Forestry prices also increase by less than 1%. The changes in prices of meat and forestry products are sensitive to assumptions about the ease of land conversion and the yield of biofuels crops. Changes in selected agricultural prices are found in Figure 7.

Internationally, prices of all agricultural prices fall because of the decrease in the world oil price. Because we assume that other countries do not have RFS policies in place in our scenario, international consumers can switch more easily from biofuels to cheaper oil, contributing to the decline in prices of biofuel crops. The US will import more of these crops as well as the final biofuels products.

4.3 Land use

The increase in the production of cellulosic ethanol will require land to be used for the cultivation of switchgrass, a crop that does not appear in the baseline. Forcing a significant amount of land into this crop will raise land prices and reduce the land available to other sectors. The amount of land used by the other agricultural sectors in the US decreases by 8-12%. Land used in forestry and livestock in the US declines by over 9%. Globally, pastureland and forest decrease by less than one percent in area by region. Figure 8 presents the change in land use for livestock, forestry, and three crops in the US. Land use change in Brazil and Europe are also shown for comparison.

5. Conclusions

Our analysis indicates substantial use of crops in the biofuels sectors due to RFS2 implementation. Though the increased demand for feedstock crops displaces crops away from food and feed sectors, it also substantially increases production and acreage in the U.S. and other regions of the world. The resulting increased demand for additional cropland leads to degradation of pastureland and deforestation globally, contributing to indirect land use change due to RFS2 implementation. In the wake of rising food prices, role of RFS2 mandate on change in food prices and consumption pattern across the regions offer useful implications.

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Appendix

Table A1. Aggregation of Regions in the ADAGE-BIO Model.

No.	*ADAGE-Code*	*Region Description*	*Comprising GTAP regions*
1	**AUS**	Oceania	Australia; New Zealand.
2	**CHN**	China, Hong Kong	China; Hong Kong.
3	**JPN**	Japan	Japan
4	**KOR**	Korea	Korea
5	**IDN**	Indonesia	Indonesia
6	**MYS**	Malaysia	Malaysia
7	**THA**	Thailand	Thailand
8	**IND**	India	India
9	**XAS**	Rest of South and S. East Asia	Taiwan; Philippines; Singapore; Vietnam; Bangladesh; Rest of Oceania; Rest of East Asia; Cambodia; Lao People's Democratic Republic; Rest of South East Asia; Pakistan; Sri Lanka; Rest of South Asia.
10	**CAN**	Canada	Canada
11	**USA**	United States	United States of America.
12	**MEX**	Mexico	Mexico
13	**ARG**	Argentina	Argentina
14	**BRA**	Brazil	Brazil
15	**ELM**	Latin American Energy Exporters	Bolivia; Colombia; Ecuador; Paraguay; Venezuela.
16	**XLM**	Rest of Latin America & Caribbean	Rest of North America; Chile; Peru; Uruguay; Rest of South America; Costa Rica; Guatemala; Nicaragua; Panama; Rest of Central America; Caribbean.
17	**EUR**	European Union 27	Austria; Belgium; Cyprus; Czech Republic; Denmark; Estonia; Finland; France; Germany; Greece; Hungary; Ireland; Italy; Latvia; Lithuania; Luxembourg; Malta; Netherlands; Poland; Portugal; Slovakia; Slovenia; Spain; Sweden; United Kingdom; Bulgaria; Romania.
18	**XEF**	Rest of Western Europe	Switzerland; Norway; Rest of EFTA; Ukraine.
19	**XER**	Rest of Eastern Europe	Rest of Europe, Rest of Eastern Europe; Albania; Belarus; Croatia.
20	**RUS**	Russia	Russia
21	**XWS**	Western Asia	Rest of Western Asia; Kazakhstan; Kyrgyzstan; Rest of Former Soviet Union; Armenia; Georgia; Iran; Turkey.
22	**ZAF**	South Africa	South Africa
23	**XNF**	Northern Africa	Rest of North Africa; Egypt; Morocco; Tunisia.
24	**XWF**	Western and Central Africa	Nigeria; Rest of Western Africa; Senegal; Central Africa; South-Central Africa.
25	**XAF**	Rest of East Africa and SACU	Ethiopia; Madagascar; Malawi; Mauritius; Mozambique; Tanzania; Uganda; Zambia; Zimbabwe; Rest of Eastern Africa; Botswana; Rest of South African Customs Union.

Table A2. Aggregation of Sectors in the ADAGE-BIO Model

No.	*ADAGE-code*	*Description*	*Comprising sectors*
1	**PDR**	Paddy rice	pdr
2	**WHT**	Wheat	wht
3	**CORN**	Corn	corn
4	**GRON**	Rest of Cereal Grains	gron
5	**SOYB**	Soybean	soyb
6	**RAPM**	Rape-Mustard	rapm
7	**PLMK**	Palm-Kernel	plmk
8	**OSDN**	Rest of Oilseeds	osdn
9	**SCANE**	Sugarcane	scane
10	**SBEET**	Sugarbeet	sbeet
11	**OCR**	All other Crops	ocr, pfb, v_f
12	**LIV**	Livestock	ctl; oap; rmk; wol; fsh
13	**FRS**	Forestry	frs
14	**MEA**	Meat	cmt, omt
15	**VOL**	Vegetable Oils	voln
16	**OMEL**	Veg Oil-meal	omel
17	**OFD**	Other foods products	ofdn, mil, pcr, sgr, b_t
18	**COL**	Coal	coa
19	**CRU**	Crude Oil Extraction	oil
20	**ELE**	Electricity and heat	ely [CONV (conventional fossil electricity), RNW (renewable electricity)]
21	**GAS**	Natural Gas	gas, gdt
22	**OIL**	Refined Petroleum	p_c
23	**CETH**	Corn Ethanol	ceth
24	**DDGS**	DDGS	ddgs
25	**WETH**	Wheat Ethanol	weth1
26	**SCET**	Sugarcane Ethanol	sceth2
27	**SBET**	Sugarbeet Ethanol	sbeth2
28	**SYBD**	Soy Biodiesel	sbiod
29	**RPBD**	Rape-Mustard Biodiesel	rbiod
30	**PLBD**	Palm-Kernel Biodiesel	pbiod
31	**MIN**	Mining	omn
32	**CNS**	Construction	cns
33	**EIM**	Energy-intensive manufacturing	PAP (ppp); crpn; nmm; PRI (i_s, nfm);
34	**MAN**	Other Manufacturing	cns; MIN (omn); TEX [tex, APP(wap), lea]; lum, FAB (fmp), TRQ (mvh, otn); ELQ (ele); MAC (ome); MSC (omf).
35	**SRV**	Services	SRV (trd, wtr, osg, cmn, trd, ofi, isr, obs, ros, osg); dwe; HLT (health service)
36	**TRN**	Transportation	otp, wtp, atp
37	**ICEV**	Personal vehicles	internal combustion engine vehicles
38	**CSTE**	Corn-Stover based Cellulosic Ethanol	
39	**SWGE**	Switchgrass based Cellulosic Ethanol	
40	**MSCE**	Miscanthus based Cellulosic Ethanol	
41	**CELD**	Advanced Cellulosic Diesel	

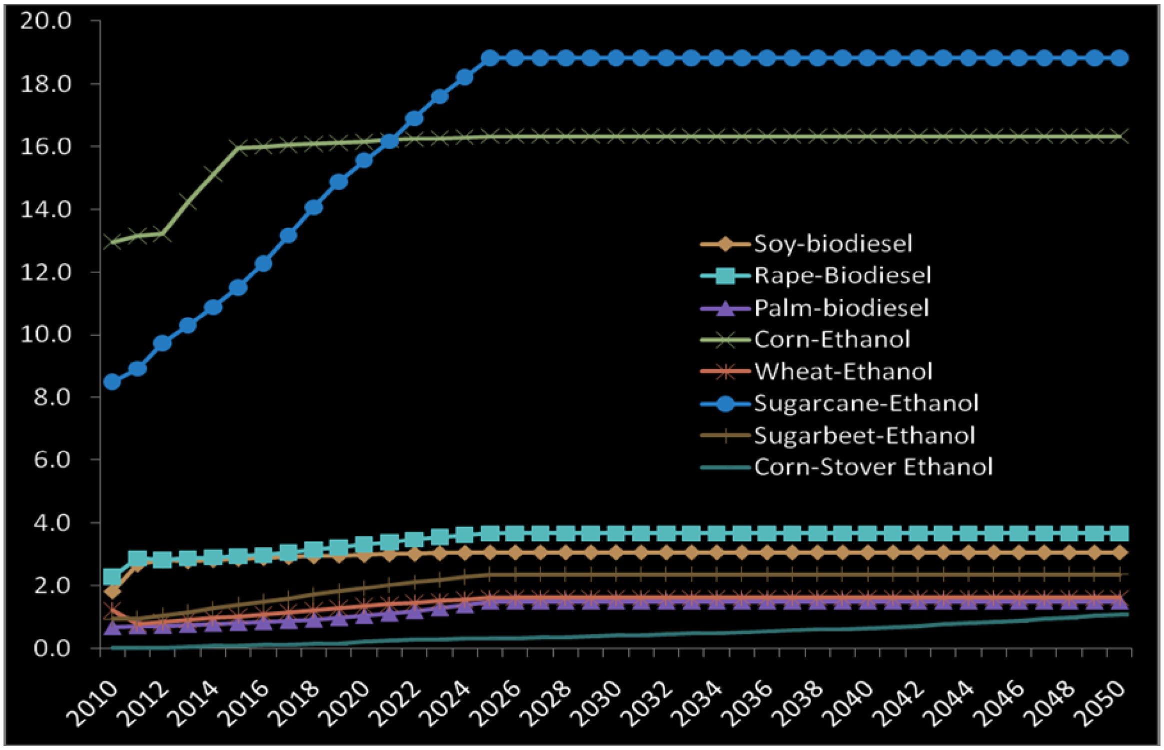

Figure A1. Baseline projections of global biofuels production (billion gallons).
Source: Authors' calculations.

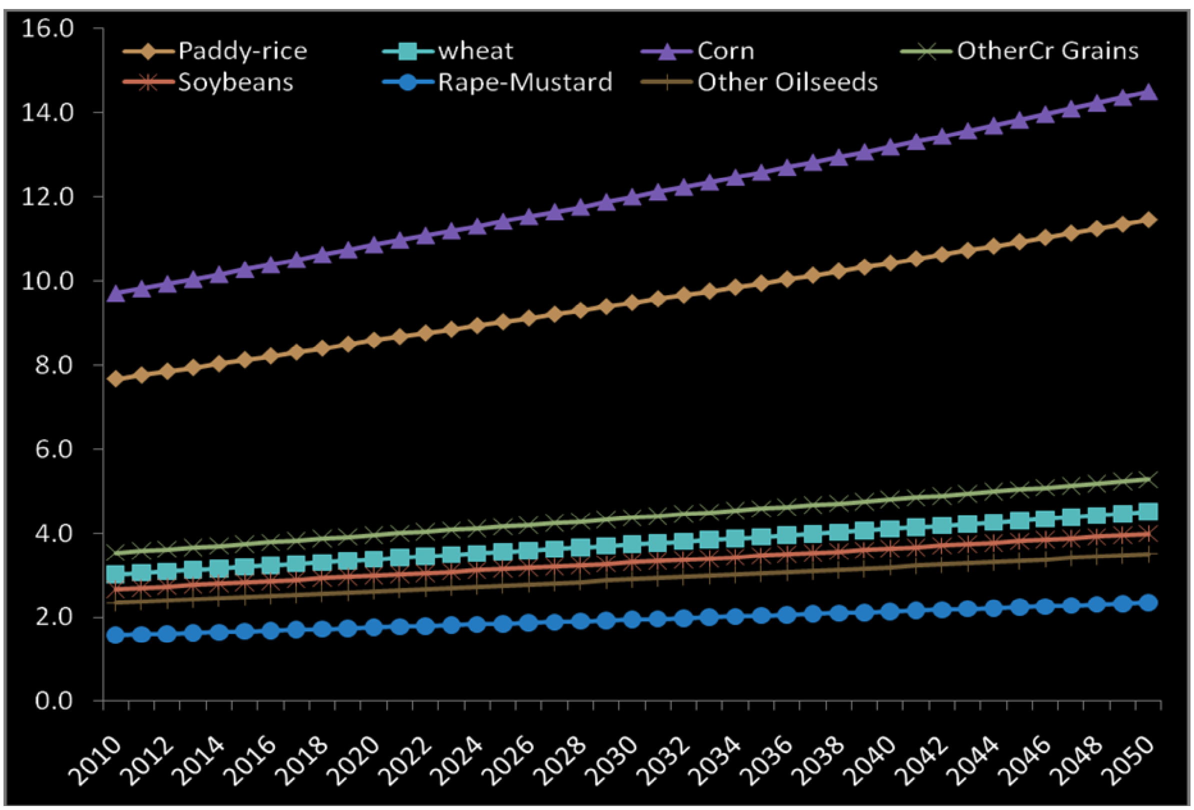

Figure A2. Baseline projections of crops' yield in the U.S. (MT/ha).
Source: Authors' calculations.