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The Net Global Effects of Alternative U.S. Biofuel Mandates

Fossil Fuel Displacement, Indirect Land Use Change, and the Role of Agricultural Productivity Growth

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Executive Summary

One of the declared objectives of U.S. biofuel policy is the reduction of greenhouse gas (GHG) emissions from fossil fuel combustion, but many studies have questioned whether such a reduction would actually occur and, if so, how large it would be. This report describes the global market, land use, GHG emissions, and nitrogen use impacts of the U.S. Renewable Fuel Standard (RFS2) and several alternative biofuel policy designs, which differ in terms of mandate magnitude and feedstock composition, over the 2010–2030 period. Analysis of the scenarios relies on GLOBIOM, a global, multisectoral economic model based on a detailed representation of land use. This model allows researchers to track shifts in land use from one region to another through variations in trade flows as well as to pinpoint intensification of agriculture through changes in management practices. The analysis reveals that RFS2 would substantially increase the portion of agricultural land needed for biofuel feedstock production. U.S. exports of most agricultural products would decrease as agricultural market dynamics change. Production would increase in other exporting regions, which would expand their exports, and in importing regions, which would face rising agricultural prices. Trade shifts would increase land conversion and GHG emissions: if the level of biofuels mandated by the government increased by 50%, more than 13 million hectares of additional land would be pressed into agricultural service worldwide, a land conversion that would release approximately 36 million tons of equivalent carbon dioxide (CO_2) per year.

In addition, RFS2 and some biofuel policy alternatives could significantly ratchet up global fertilizer use to satisfy additional production needs. The additional GHG emissions due to increased fertilizer use (primarily nitrous oxide, N_2O) could be greater than those arising from land use change. With a 50% increase in the biofuel mandate, global GHG emissions from fertilizer use rise by 1.4%.

The overall net effect of U.S. biofuel policy depends on the balance between the reduction in national GHG emissions achievable with an increase in U.S. biofuel production and additional GHG emissions in the rest of the world. As a first-order effect, biofuels cause a reduction in emissions from the fossil fuels they displace. From that initial effect, one must factor in the emissions caused by biofuel production and processing as well as the indirect land use change caused by shifts in commodity production when agricultural feedstocks are used for biofuels. Taken together, we find that within the United States, higher levels of the mandate mean lower net emissions. The fossil fuel reductions are greater than the processing and land use emissions *within the United States*. However, when emissions from the rest of the world are considered, the net global reductions of having more U.S. biofuel are close to zero (no net GHG benefits) and even positive (higher global GHG emissions) in some cases.

The net emissions effects are slightly asymmetric depending on whether we are looking at reductions or increases in the stringency of the mandate. If the mandate level is reduced below what is called for by RFS2, this causes emissions outside the United States to reduce proportionally with the increase in U.S. emissions, which includes forgone reductions in emissions from displaced fossil fuels such as gasoline. Under such a scenario, the net change in global GHG emissions is essentially zero from changing the U.S. mandate. However, raising the current RFS2 mandate leads to growth in emissions outside the United States—growth that exceeds reductions in U.S. fossil fuel emissions, leading to a net increase in emissions globally.

The feasibility of achieving the legislated share of second-generation biofuels (such as lignocellulosic varieties) is questionable. Therefore, the present analysis examined the effects of relaxing the second-generation share requirements. The analysis revealed that holding the level of the RFS2 mandate constant but increasing the share of conventional corn-based ethanol used to meet it leads to a net increase in emissions. In fact, global emissions would be about 30 million tons (Mt) CO_2e higher under these relaxed cellulosic share conditions (called "RFS2 high corn" in this analysis) than they would be if the total mandate were reduced by 50%. Thus, policy stipulations governing the composition of the mandate are just as important as (or, in some cases, more important than) those concerning the volume of the mandate.

A sensitivity analysis shows that the magnitude of the impacts of U.S. biofuels policy depends on the evolution of future agricultural productivity. The indirect land use change (ILUC) emissions factor (relative to fossil fuel displacement effects) would be 30% higher for the RFS2 mandate if future yield growth outside of the United States were 50% lower than assumed baseline yield growth. Moreover, the commonly expressed concern that biofuels could compete with food production is supported by increased food prices in and dependence on food imports by several developing countries.

Consequently, enhancing productivity increases in agriculture in the United States and the rest of the world should be a necessary condition for further development of biofuels. This finding argues for flexible programs favoring investments

in agricultural research and technological diffusion over mandatory targets increasing pressure on agricultural markets. Such programs should focus in particular on technologies that increase the efficiency of, or provide substitutes for, synthetic fertilizers that emit nitrous oxide, a potent greenhouse gas.

This study contributes to the emerging literature on the net effects of biofuel policy in unique ways. It connects detailed variations in a very specific and significant policy in the United States (RFS2) with a full range of commodity market, land use, and GHG effects using a global economic model of land use. Recognizing that the RFS2 mandate could be altered in either direction, this study seeks to examine the impacts of across-the-board contraction or expansion of the mandate, as well as changes in its composition by biofuel type. Moreover, we show the importance of future yield growth in determining the land use needs and GHG consequences. As such, we believe these findings provide useful insights into the effects of scale and scope on biofuel policy outcomes and underscore the importance of global feedback effects from local policies.

Introduction

One of the declared objectives of U.S. biofuel policy is reduction of greenhouse gas (GHG) emissions from fossil fuel combustion (OECD 2008). However, many scientific studies have questioned the effectiveness of biofuel mandates, and the environmental outcome of biofuel programs remains the subject of intense debate (e.g., De Santi et al. 2008; Pimentel and Patzek 2005; Robertson et al. 2008).

The Kyoto Protocol (the GHG emissions reduction agreement under the United Nations Framework Convention on Climate Change) considers the use of biofuels to be carbon-neutral because of photosynthesis during biomass growth; therefore, the only GHG emissions accounted for are those occurring along the production chain. Life-cycle analyses (LCAs) have identified the GHG balances for biofuel pathways, taking into account emissions from field to tank (Bureau et al. 2010; Edwards et al. 2004). Some studies dispute these balances (Crutzen et al. 2008; Scharlemann and Laurance 2008). Other studies highlight an emissions source not included in LCAs: diverting biomass traditionally used for food and feed for energy can shift food production to other areas, thereby increasing incentives for conversion of natural ecosystems (Fargione et al. 2008; Searchinger et al. 2008). Emissions associated with this indirect land use change (ILUC) could potentially revert the GHG balance of biofuel policies.

This report complements the Baker et al. (2011) analysis of the domestic effects of U.S. biofuel policies on GHG emissions and nitrogen use by accounting for the policies' international spillover effects and net global consequences. For several reasons, ILUC effects from international sources could be particularly significant in the case of U.S. biofuel expansion policies. First, the United States is a leading producer of agricultural products and a major actor in international markets for oilseeds and cereals. In 2007, U.S. exports represented more than half of the total corn exports traded in international markets and 22% of wheat exports (FAO 2008). Moreover, the United States is the world's leading soybean producer and exporter. Its exports amount to 40% of total soybeans exports, 10% of soybean cakes exports, and 9% of soybean oil exports (FAO 2008). Second, in the United States, as in most other member countries of the Organisation for Economic Co-operation and Development (OECD), cropland expansion is limited by previous expansion (most arable land is already in agricultural production), the costs of converting forestland to farmland, and the opportunity costs of competing urbanized and developed land uses. In addition, some significant restrictions have been set on land conversion and existing conservation programs could limit further expansion (such as the U.S. Conservation Reserve Program).

By contrast, large natural areas in the southern hemisphere have no protection status or are left vulnerable because of the high costs of enforcing protection (Robalino and Herrera 2009). Many countries with large forests have become leading agricultural exporters, increasing pressure on those forests and other natural resources. Relatively high agricultural prices increase the risk of deforestation and active agricultural trade has been identified as a powerful discriminator between countries with relatively high forest loss and those with relatively low forest loss (DeFries et al. 2010). Some other developing countries have become major food importers, raising the exposure of a portion of their population to international price developments. Given demographic pressure and economic integration, agricultural production throughout the world will probably become increasingly reactive to market signals.

Agricultural production not only consumes land but also intensifies land management, sometimes with negative environmental effects. Field application of nitrogen-based fertilizers, for example, leads to the emission of nitrous oxide (N_2O), a greenhouse gas that is approximately 300 times as potent as carbon dioxide (CO_2). Fertilizer application also can lead to the runoff and leaching of residual nitrogen, which can diminish water quality in recipient surface water and groundwater systems (Robertson and Vitousek 2009). Irrigation, another form of agricultural intensification, can divert water resources to field application.

Because U.S. biofuel policy is likely to trigger impacts in other parts of the world, it should be analyzed in a framework that takes into account increased pressure on land globally. Hence, this study models the global agricultural market, land use, and GHG impacts of current U.S. biofuel policy. It illustrates the sensitivity of these impacts to alternative biofuel mandates, which vary by volume and fuel mix. Additional analysis tests the sensitivity of these impacts to alternative assumptions about future agricultural productivity growth.

Several alternative modeling approaches have simulated land use responses to biofuel expansion and resulting emissions. Searchinger et al. (2008) was the first to propose an estimate of ILUC emissions related to U.S. biofuel consumption. That study uses the FAPRI-CARD agricultural economic forecasting model to examine various feedstocks for ethanol production. It calculates that ILUC would represent 104 g CO_2 per megajoule (MJ) for corn ethanol alone if the emissions from land clearing were amortized over a 30-year period. Assuming that a 20% life-cycle GHG emissions savings rate is associated with corn ethanol, corn for ethanol production would need to be grown for 167 years just to repay the initial land use change emissions. Other feedstocks for ethanol also have negative GHG effects. Growing miscanthus instead of corn in fertile areas would generate 111 g CO_2 per MJ and require 52 years to repay (thanks to a comparatively high LCA direct savings coefficient). Sugar cane grown in Brazil would require only 4 years to repay if expansion occurs into grassland, but 45 years if tropical forest is converted.

Keeney and Hertel (2009) argued that the Searchinger et al. study should have considered the role of endogenous yield response to price change. Indeed, Searchinger asserted an alternative scenario wherein only 20% of supplemental demand could be obtained from increased corn yield, which had already decreased the payback time to 34 years. Keeney and Hertel assert that endogenous yield response could be much higher; their simulations with a variant of the Global Trade Analysis Project (GTAP) model indicate that a third of the additional demand could be covered through crop yield increases. Using this model, Keeney and Hertel provide an analysis of U.S. biofuel mandates more comprehensive than that of Hertel et al. (2010). They find a 30-year ILUC factor (land use change emissions per unit of biofuel averaged over a 30-year period) of 27 g CO_2 per MJ, i.e., a quarter of the value found by Searchinger et al. Despite the substantial quantitative difference in results, both Hertel et al. and Searchinger et al. come to the same qualitative conclusion that corn ethanol production remains a net source of GHG emissions for some time once ILUC emissions are counted.

The GTAP model has also been used in a wider set of estimations for the California Air Resources Board (CARB) to assess the net impact of California's Low Carbon Fuel Standards regulation. The CARB study references the following ILUC values: 30 g CO_2 per MJ for corn ethanol, 46 g CO_2 per MJ for sugarcane ethanol, and 62 g CO_2 per MJ for soybean biodiesel (CARB 2009). By comparison, total GHG emissions from gasoline combustion are approximately 73 g CO_2 per MJ. Depending on the processing pathway (type of refinery, location of production), direct emissions can vary significantly, and overall emissions from feedstock use can be compared. For example, corn ethanol produced in the U.S. Midwest from wet mill refineries powered on coal would yield a negative energy balance (increased GHG emissions), whereas corn ethanol refined in California in dry mill refineries powered on natural gas would generate GHG savings by lowering direct emissions 50%. To complement these computations, Britz and Hertel (2011) used the CARB modeling framework to examine rapeseed-related ILUC from rapeseed oil use in Europe. They find a 47g CO_2 per MJ ILUC factor, confirming that biodiesel can induce substantial land use change emissions, mostly due to lower yield of biodiesel feedstocks.

The most recent and comprehensive assessment of the impacts of U.S. biofuel feedstocks remains the regulatory impact analysis of the RFS2 regulation performed by the U.S. Environmental Protection Agency (EPA) and released in 2010. Using several models (FAPRI, GREET, FASOMGHG), the exercise computed ILUC factors for many first- but also second-generation pathways. EPA's estimate of the ILUC factor for corn ethanol is identical to CARB's estimate, at 30 g CO_2 per MJ, but is lower for soybeans than CARB's, at 40 g CO_2 per MJ over 30 years (EPA 2010). According to EPA, the ILUC factor of switchgrass ethanol is 14 g CO_2 per MJ, and that of sugar cane ethanol is 4 g CO_2 per MJ. EPA's evaluation benefited from a relatively detailed set of data for carbon stock changes and cropland expansion dynamics, but it also revealed the high sensitivity of results to key modeling assumptions. For example, the estimate for soybean ILUC could vary from 20 to 70 g CO_2 per MJ, depending on the calibration of historical land use change data and land carbon emission factors for a 95% confidence interval. A shortcoming of the EPA analysis, noted by Baker et al. (2011), is that it evaluates the impact of alternative fuels one feedstock at a time, but the RFS2 mandate will likely lead to simultaneous production shifts in multiple types of biofuels produced from a variety of feedstocks. The compounding effect of increasing the volume of multiple biofuels one at a time suggests a less GHG-efficient renewable fuels portfolio than might be accomplished if managed together.

The uncertainty of ILUC has been explored with a simplified model in Plevin et al. (2010). Relying on a set of elementary assumptions built on literature outcomes, the authors showed that the 95% confidence interval for carbon stock, model behavior, or amortization period would yield ILUC factors ranging from 21 to 142 g CO_2 per MJ per year. More strikingly, they find an upper bound of 340 g CO_2 per MJ, much higher than all previous estimates; their lowest estimate would not fall below 10 g CO_2 per MJ.

Most other assessments of non-U.S. regions have confirmed the findings of U.S.-oriented studies. Using the MIRAGE-BioF model, Al Riffai et al. (2010) found a 20-year ILUC factor of 18 to 20 g CO_2 per MJ for European Union biofuel policy, depending on trade assumptions. Using the same model, Havlík et al. (2011) focused on global biofuel expansion and found 30-year ILUC coefficients for first-generation feedstocks of 53 to 62 g CO_2 per MJ, depending on scenarios. They also found that second-generation feedstocks from short-rotation plantations can lead to overall GHG savings if biomass is sourced primarily from sustainably managed forests. Melillo et al. (2010) present a much darker picture of potential for second-generation feedstocks. Their examination of cellulosic biofuel crops indicated a 30-year ILUC factor of 180 to 190 g CO_2 per MJ, more than double the displaced gasoline emissions, depending on the characteristics of land use expansion. These results clearly illustrate the variability of outcomes with respect to feedstocks, amortization period, and crop-growing region.

Most modeling exercises to date have been based on top-down approaches (computable general equilibrium models—CGEs—such as GTAP, EPPA, or MIRAGE) or on model linkages (such as those in the EPA 2010 study). Both techniques suffer from important limitations. CGEs lack robust sectoral supply-side detail, because they are based mainly on social accounting matrices for the entire economy and rarely incorporate a precise account of input-output physical constraints and process technologies. Model linkages perform better on this score thanks to refined national models, but they often reflect theoretical and aggregation inconsistencies. For example, the EPA (2010) study could not replicate similar production and export levels for some commodities with the FASOMGHG and FAPRI models.

The GLOBIOM model (Havlík et al. 2011) overcomes these shortcomings by presenting a detailed description of agricultural production processes and covering the whole world in a fully integrated setting. The present analysis uses GLOBIOM to investigate the impact of the U.S. RFS2 biofuel policy (as defined by the Energy Independence and Security Act in 2007) on global GHG emissions from agriculture and land use change and on nitrogen use over the 2010–2030 period. To isolate the specific effects of the policy, the model is run for multiple levels of biofuel mandates. The results are subjected to a sensitivity analysis with respect to crop yield growth. To the extent possible, GLOBIOM was harmonized with the FASOMGHG model with respect to basic assumptions and scenario definition to deliver a global picture consistent with the U.S.-focused report by Baker et al. (2011).[1]

This report explains the methodology of the analysis. It then presents several biofuels policy scenarios and simulation results, which are explained in detail. It concludes with a discussion of the results in light of previous studies and offers policy recommendations.

Methodology

The Global Biosphere Management Model (GLOBIOM) was developed by and is used at the International Institute for Applied Systems Analysis (IIASA). A global recursive dynamic partial equilibrium model, GLOBIOM is designed to aid policy analysis of land use competition among the major land-based production sectors, particularly agriculture, forestry, and bioenergy. It provides for a detailed representation of each sector, accounting for about 20 of the most globally important crops, a range of livestock production activities, major forestry commodities, and multiple bioenergy transformation pathways.

GLOBIOM is an optimization model wherein market equilibrium is determined by choosing land use and processing activities to maximize social welfare (i.e., the sum of producer and consumer surplus) subject to resource, technological, and policy constraints. Countries are assigned to 1 of 28 regions (see appendix). Prices and international trade flows are endogenously determined at the level of these regions.

Land use

The supply side of the model reflects a detailed spatial resolution that accounts for land heterogeneity. The model draws from a global database with information on soil types, climate, topography, land cover, and crop management (Skalsky et al. 2008). These data have been harmonized at the simulation unit level, which is defined by the intersection of country boundaries, altitude, and slope and soil classes within a 50 x 50 km grid. GLOBIOM disaggregates available land into several land cover classes, which can (or cannot) be used for production. Forest land is made up of two categories (unmanaged forest and managed forest); the other categories include cropland, short-rotation tree plantations, grasslands (managed grasslands), and "other natural vegetation" (including unused grasslands). The model allows land cover/use conversions, but the total land area spanning all categories remains fixed. The model is recursive dynamic in the sense that changes in land use made in one period alter land availability in the various categories in the next period.

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[1] Work on both reports was performed simultaneously under one project supported by the David and Lucile Packard Foundation.

Bioenergy

Resources for the different types of bioenergy products can be sourced from cropping and forestry activities. First-generation biofuels include ethanol made from corn, sugarcane, and wheat, and biodiesel made from rapeseed, palm oil, and soybeans. Processing data are based on Haas et al. (2006) for biodiesel and on Hermann and Patel (2007) for bioethanol. Data on the quantity of by-products obtained through biofuels processing and on the rate that by-products are substituted for traditional livestock feeds are taken from the Gallagher review (RFA 2008). The livestock industry's use of biofuel by-products as protein and energy sources can to some extent mitigate the price impacts of biofuel production and reduce the demand for cropland (Taheripour et al. 2010). The value of biofuel by-products also decreases the production cost per unit of biofuel and thus influences choice of feedstock. DDGS (dry distiller grains with solubles) from corn and wheat, soybean meals, and rapeseed meals are explicitly modeled. Biomass for second-generation biofuels is sourced from existing forests, wood-processing residues, or short-rotation tree plantations. The model can choose the most efficient biofuel pathway portfolio for a given level of exogenous demand (mandate).[2]

GHG emissions accounting

GLOBIOM accounts for the major GHG emissions and sinks related to agriculture and forestry, particularly emissions related to crop cultivation, land use, livestock, and fossil fuel substitution. The calculation of emissions coefficients depends on the emissions source. Soil N_2O emissions from application of synthetic fertilizers are calculated according to the 1997 International Panel on Climate Change (IPCC) guidelines on the basis of fertilizer use as simulated in EPIC. CO_2 emissions related to fertilizer production are also computed proportionate to nitrogen and phosphate input using emissions factors from the UK Renewable Fuel Agency (RFA 2008). Coefficients for methane (CH_4) emissions from rice production are derived from EPA (2006); CH_4 emissions from enteric fermentation and N_2O emissions from manure management are estimated with the RUMINANT model. CO_2 savings coefficients for the various bioenergy paths are calculated using parameters from Edwards et al. (2004, updated 2007) and RFA (2008). GHG accounts of land use change activities are based on the carbon contents in equilibrium states of the different land cover classes. Carbon content in above- and below-ground living forest biomass is taken from Kindermann et al. (2008), and carbon content in the biomass of short-rotation plantations is calculated on the present study's estimates of the plantations' productivity. For parameterization of carbon in grasslands and in other natural vegetation, the biomass map of Ruesch and Gibbs (2008) is used. CO_2 coefficients for emissions and sinks due to land use change are calculated as the difference between the carbon content of the initial land cover class and that of the new class. Only carbon in the above- and below-ground living biomass is considered, because no reliable data on soil organic carbon are available.

International trade

Imported goods and domestic goods are assumed to be identical (homogenous), meaning that the only differences in their prices are due to trading costs, but as a spatial equilibrium model, GLOBIOM can represent bilateral trade flows. This analysis includes both tariffs and transportation costs differentiated among products and trading partners. The tariffs come from the MAcMap database[3] (Bouët et al. 2004). To compute transportation costs, on which data are lacking, the analysis uses the coefficients between freight rates and distance and estimates by Hummels (2001) of goods' weight-over-value ratio. The trade calibration method proposed by Jansson and Heckelei (2009) is applied to reconcile observed bilateral trade flows, regional net trade, prices, and trading costs for the base year. Finally, non-linear trade costs are assumed when trade costs increase with the amount of traded quantities.

International trade in biofuels has been limited, representing 8% of ethanol and 12% of biodiesel world total production in 2007 (OECD 2008). Furthermore, these biofuels were mainly produced from domestic feedstocks. For instance, an estimated 70% of European biodiesel production has come from domestic rapeseed (USDA 2010). With the exception of Brazil, most biofuel-producing countries impose high import tariffs on ethanol. Moreover, biofuels must comply with fuel standards, which also influence choice of feedstock. More generally, domestic support to farmers and to the biofuel industry provides a strong element of protection (Steenblick 2007). Therefore, this analysis allowed for no international trade in biofuels except for ethanol imports from Brazil to the United States. For this particular transaction, the analysis

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[2] Note that GLOBIOM currently does not handle cellulosic ethanol from perennial bioenergy crops such as switchgrass and miscanthus, or use of crop residues for energy conversion. This differs from Baker et al. 2011, which projects that a large portion of the U.S. cellulosic mandate will be met through use of switchgrass. Inclusion of dedicated energy crops such as switchgrass could increase land use competition further, potentially amplifying the market and international LUC effects herein. However, use of crop residues can ameliorate this effect to an extent as harvesting residues for biofuel does not compete directly with food production.

[3] Tariffs on ethanol and biodiesel in OECD countries are taken from the Global Subsidies Initiative (Steenblik et al. 2007).

harmonized its assumptions about cellulosic ethanol mandates and expected ethanol imports under the RFS2 legislation as discussed in the U.S. EPA RIA (U.S. EPA 2010).

Productivity change

Productivity change arises in the model as a combination of exogenous productivity growth over time and endogenous yield change. The latter comes about through management system changes and movement of crop production to relatively more or less suitable areas. This analysis assumes that an exogenous productivity growth of 1% per year is uniform across regions and crops outside of the United States. Although this growth approximates the average productivity development observable between 2000 and 2010, it should be considered somewhat optimistic. For U.S.-specific yield growth, numbers applied in Baker et al. (2011) have been adapted as detailed below. This exogenous productivity is coupled with crop-specific management intensification, including increased use of fertilizer and other factors of production (for the United States). Furthermore, the analysis distinguishes four crop management systems—subsistence agriculture, low-input rain-fed agriculture, high-input rain-fed agriculture, and high-input irrigated agriculture—and allows for switches among them (You and Wood 2006).

Spatially explicit yields for each crop and each management system as well as input requirements have been estimated using the biophysical crop growth model EPIC (Izaurralde et al. 2006). For livestock, only endogenous productivity growth through changes in the structure of management systems is represented. Livestock management systems have been defined according to the livestock production systems classification developed by the International Livestock Research Institute and the Food and Agriculture Organization (updated Seré and Steinfeld 1996). Input-output coefficients have been computed with the RUMINANT model for ruminants (Herrero et al. 2008) and derived from a literature review for monogastrics (pigs, poultry, and other livestock with one stomach). The analysis assumes no change in the productivity of managed forests.

Exogenous demand drivers

Other principal exogenous drivers are gross domestic product (GDP) and population change as well as bioenergy demand. The present analysis uses the most recent projections from the World Energy Outlook (IEA 2010) for per capita GDP and population growth. Projections for bioenergy demand (with the exception of U.S. biofuel demand) are taken from the World Energy Outlook (WEO) new policies scenario, which assumes that countries will introduce new measures to implement announced climate and energy policy commitments. The analysis relies on the FAO-projected demand for agricultural product aggregates, including per-capita calorie consumption (Alexandratos et al. 2006), as a lower bound for agricultural demand.

U.S. data harmonization

Given the focus on U.S. biofuel policy, the present analysis pays particular attention to harmonization of rates of exogenous crop-yield growth, land conversion for development, and biofuel scenarios as simulated by Baker et al. (2011) with the FASOMGHG model. In 2007, EISA increased the 2005 renewable fuels requirement (RFS1) to 36 billion gallons (2.88 EJ) by 2022. Given uncertainties in future energy demand projections and transportation sector infrastructure, long-term ethanol production is locked in at RFS-mandated levels beyond 2022. Total cellulosic ethanol is set at 13.7 billion gallons (1.1 EJ) per year at the pinnacle of RFS2. This constraint is based on the RFS2 requirement of 16 billion gallons (1.3 EJ) of cellulosic biofuels and on the EPA assumption that 2.3 billion gallons (0.2 EJ) of this amount will be satisfied with municipal and industrial waste-derived biofuels (Baker et al. 2011). The analysis assumes that sugarcane ethanol imports from Brazil will represent 10% of the total U.S. biofuel mandate after 2020 (Table 1).

Table 1. U.S. bioenergy consumption based on RFS2 mandates

	2000	2010	2020	2030
Total biofuel (in EJ *)	**0.17**	**1.19**	**2.76***	**2.76***
First-generation biofuel	**100%**	**97%**	**59%**	**59%**
U.S. biodiesel	0%	6%	4%	4%
U.S. crop ethanol	100%	90%	45%	45%
Ethanol imports	0%	1%	10%	10%
Cellulosic ethanol	**0%**	**3%**	**41%**	**41%**

* For the purpose of simplification, the analysis assumes that the RFS2 mandate will be fulfilled as soon as 2020.
Figures do not incorporate municipal and industrial waste-derived biofuels that are not represented in the model.

In recent decades, the United States has experienced an upward trend in special use and urban areas and a downward trend in agricultural land (Lubowski et al. 2006). Because urban area expansion is not endogenously represented in GLOBIOM, the analysis calculates this expansion in each period exogenously on the basis of the 2010 Resource Planning Act (RPA) Assessment (Alig et al. 2009). Accordingly, the analysis assumes that 115,000 hectares (ha) of cropland, 92,000 ha of pasture, and 232,000 ha of forests are developed each year.

Exogenous U.S. crop-yield development reflects estimates computed for the FASOMGHG model (Beach et al. 2011). Exogenous productivity growth parameters in FASOMGHG were estimated econometrically using U.S. Department of Agriculture and National Agricultural Statistics Service statistics on crop yield from 1960 to 2009. For each commodity, yield growth (the dependent variable) is estimated as a function of time, where both linear and log-log functional forms are estimated. The analysis tested all years between 1969 and 1985 as possible structural break points using a 16-year time window within which the data can be partitioned into two intervals. Where structural breaks were found, the parameters after the break were used for yield extrapolation to represent a relatively recent trend in yield growth. The analysis identified a best-fit parameter for each commodity by minimizing the sum of squared errors over all regressions, thus choosing the optimal functional form, with or without a structural break, and optimal break year.

Results

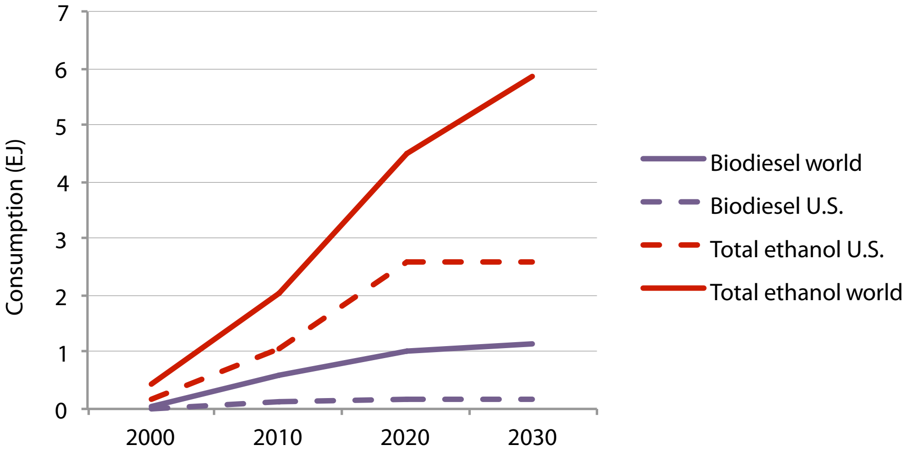
Baseline

The baseline reflects the model projections of outcomes under the business-as-usual scenario reflecting full implementation of the RFS2 and standard market and technology assumptions. Key baseline results are highlighted here.

Biofuels and biofuel feedstocks

U.S. demand accounts for more than half of the world's total bioethanol demand and 17% of total biodiesel demand. These shares drop to 44% of total bioethanol and 16% of total biodiesel in 2030 under the assumption that biofuel demand in the United States stabilizes at 2.6 EJ per year and that demand in the other regions, especially in Asia, continues to increase (Figure 1). However, U.S. demand is composed of a larger share of second-generation biofuels (41% of ethanol from cellulosic sources compared with only 6% in the rest of the world).

Figure 1. Biofuel demand in the U.S. and rest of the world (ROW) between 2000 and 2030



After full implementation of RF2 in the baseline (Table 2), the United States produces 15 billion gallons of corn ethanol (1.25 EJ), 1.5 billion gallons of soybean biodiesel (0.19 EJ), and 0.3 billion gallons of rapeseed biodiesel (0.03 EJ). To do so, the amount of corn it processes rises from 124 million tons (Mt) to 145 million tons, and the amount of soybeans, from 18 Mt to 26 Mt. The United States also imports approximately 2 Mt of rapeseed (mainly from Australia, Canada, and New Zealand) to process into biodiesel. Imported sugarcane ethanol from Brazil represents the use of 10 Mt and 160 Mt of sugarcane per year in 2010 and 2020, respectively. Production of second-generation biofuels requires an increase in cellulosic biomass from 16 million cubic meters (m^3) in 2010 to 430 million cubic meters in 2020. In 2010, this biomass is taken from sawmill wood residues, but by 2020, approximately two-thirds of the demand is met by new short-rotation tree plantations. In the rest of the world, 60% of first-generation biofuels is derived from sugarcane, 15% from corn, 13% from rapeseed, 8% from wheat, and 4% from soybeans. In 2030, quantities processed for U.S. biofuel production represent a significant share of global demand for corn (12%) and soybeans (11%).[4]

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[4] These numbers must be adjusted to take into account coproducts' return.

Table 2. Biofuel production and processed feedstock for biofuel production in the U.S. and ROW

		2000	2010	2020	2030
United States	**Biofuel production (EJ)**				
	Corn ethanol	0.18	1.07	1.25	1.25
	Soybean biodiesel	0.00	0.122	0.17	0.18
	Rapeseed biodiesel	–	–	0.03	0.03
	Cellulosic ethanol	–	0.04	1.13	1.13
	Processed quantity by feedstock				
	Corn (million tons)	20.5	123.8	144.8	144.8
	Soybean (million tons)	0.2	17.9	25.3	26.1
	Rapeseed (million tons)	–	–	2.1	1.7
	Cellulosic biomass (million m^3)		158.5	430	479.3
Rest of the world	**Biofuel production (EJ)**				
	Sugarcane ethanol	0.26	0.74	1.702	2.622
	Corn ethanol	0.01	0.07	0.22	0.42
	Wheat ethanol	–	0.16	0.31	0.33
	Soybean biodiesel	–	0.33	0.48	0.35
	Rapeseed biodiesel	0.03	0.21	0.45	0.66
	Cellulosic ethanol	–	–	–	0.58
	Processed quantity by feedstock				
	Sugarcane (million tons)	153.4	433.4	999.9	1540.5
	Corn (million tons)	0.7	8.4	25.2	48.5
	Wheat (million tons)	–	19.7	37.7	40.8
	Soybean (million tons)	–	48.7	70.1	51.7
	Rapeseed (million tons)	1.9	13.3	28.6	41.7
	Cellulosic biomass (million m^3)	–	–	–	92.8

Market conditions

Prices for most agricultural products around the globe increase until 2020 but decrease through the following decade as productivity improvements relax commodity the initial market impacts of the biofuel policy shifts. In the United States, projected prices for agricultural products in 2030 are lower than those in 2010. In 2020, prices of cotton, groundnuts (e.g., peanuts), sorghum, and soybeans are projected to peak. The price of corn increases by 6% between 2010 and 2020 before decreasing by 20% between 2020 and 2030, given high productivity-growth assumptions.

Between 2010 and 2030, U.S. corn production increases by 23%, due to the additional demand for bioenergy but also for food and feed (+25%). Two-thirds of the additional production goes to the domestic market and one-third, to international markets. In 2030, animal feeding remains the first corn use in the United States (57%), followed by biofuel processing (40%); the remaining 3% is used for human consumption. In the rest of the world, total demand for corn increases by 50% between 2010 and 2030, driven by high population growth and higher per capita meat consumption in developing countries. The United States remains the largest corn exporter over the period, even as exports from Latin American countries increase rapidly. The structure of U.S. corn external trade is also modified with a decrease of exports to Canada and Mexico and to South America and a rise in exports to the Middle East, Africa, and South Asia. However, Japan remains the first destination for U.S. corn, which it uses mainly for animal feeding. Due to corn ethanol processing, DDGS are also produced and used in the livestock sector, where they can substitute for protein meals (soybean cakes, for instance) in animal feeding. The large increase in DDGS availability, combined with the comparatively high yield growth of corn in the United States, more than offsets increased cereal prices in 2020 and stimulates production in the monogastric sector: pork and poultry meat exports increase over the period.

During the 2010–2030 period, U.S. demand for soybeans increases only 13%, despite growth in demand for soybeans for biodiesel. The reason is that demand for soybeans for animal feeding decreases as corn DDGS replaces soybean cakes. Exports are also reduced; the U.S. share of the world market falls from 42% to 30%. Exports to Europe and China drop by more than 35%, but they increase to Central America and South Asia. The reason is that Europe and China increase their domestic production of biodiesel, resulting in by-products that substitute for an increasing share of soybean imports in animal feeding. U.S. soybean production therefore increases by 4%.

Wheat production increases by 20% in the United States, in equal parts a response to higher domestic demand and higher exports. Internal demand is fostered by growth of the monogastrics sector. Exports decrease to Mexico but increase everywhere else, especially in Southeast Asia (+96%) and sub-Saharan Africa (+71%), where demand for wheat increases dramatically (+37% and +71%, respectively). The Middle East and North Africa remain the first destination of U.S. wheat exports (more than 7 Mt in 2030). Internationally, traded quantities expand by 25% by 2030, meaning that the United States remains the leading supplier with approximately 30% of world trade, followed by Australia, Canada, and former USSR countries.

Land use

The main land use changes in the United States are driven by development of undeveloped land and expansion of short-rotation tree plantations to fulfill bioenergy targets. In total, these two land use types gain 21 Mha between 2010 and 2030. Total agricultural land decreases by 19 Mha; conventional cropland accounts for more than 70% of the loss. Short-rotation tree plantations replace 8.5 Mha of conventional cropland, while 3.6 Mha are developed. Total cultivated area is reduced for almost all crops drops: -13% for corn area (4.5 Mha), -16% for wheat area (2.3 Mha), and -14% for soybean area (3.0 Mha). The forest area under exploitation increases by 18%.

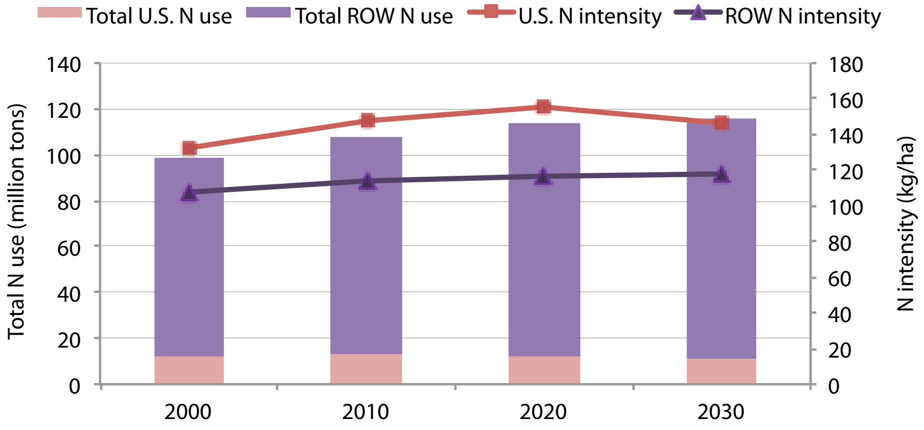
In the rest of the world, agricultural land area increases by 8%. Europe and former USSR countries experience a decrease in cropland area. Sub-Saharan Africa, North Africa, and the Middle East experience a 20% increase; Latin America, a 16% increase; and Southeast Asia, a 13% increase. The average deforestation rate over 2010-2030 is about 0.17% per year.

Nitrogen use and intensity

Total use of nitrogen has leveled off from historic increases of the past several decades and is expected to decrease slightly between 2010 and 2030 in the United States (Figure 2). This projection is explained by technological improvements leading to higher yields with less than proportional increases in fertilizer requirements as well as by decreased cropland area. The average nitrogen use per hectare of cultivated crop (nitrogen intensity) increases between 2010 and 2020 and then decreases in 2030, due to management changes and the composition effect among crops (as crop mix patterns change over time in response to the biofuel policy). These U.S. projections for nitrogen are largely consistent with the finding of Baker et al. (2011) that nitrogen use will vary slightly through 2030. Nitrogen intensity increases substantially for wheat (+12%) and barley (+21%) but is stable for corn and decreases for soybeans and cotton.

In the rest of the world, nitrogen use rises by 9% between 2010 and 2030. This projection reflects a huge nitrogen consumption increase in the Middle East and North Africa (+43%) and in sub-Saharan Africa (+40%). Nitrogen consumption decreases in Europe (-5%) and in the former USSR countries (-1%).

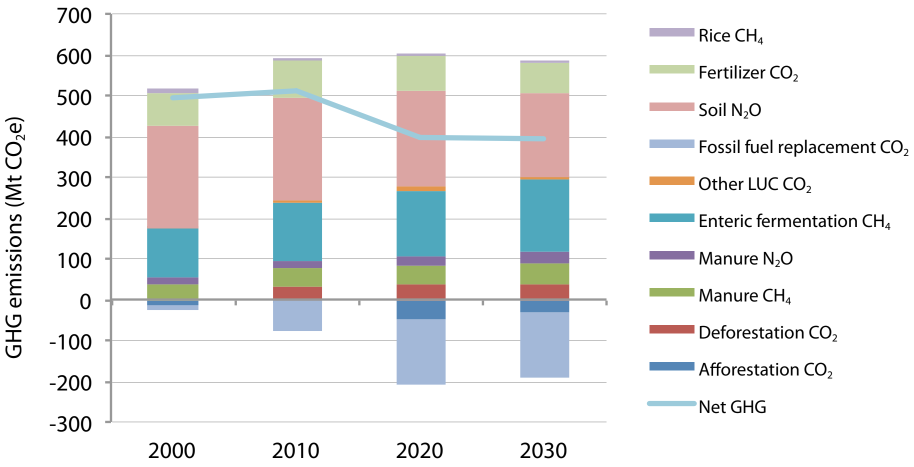
Figure 2. Evolution of nitrogen use in the U.S. and ROW



GHG emissions

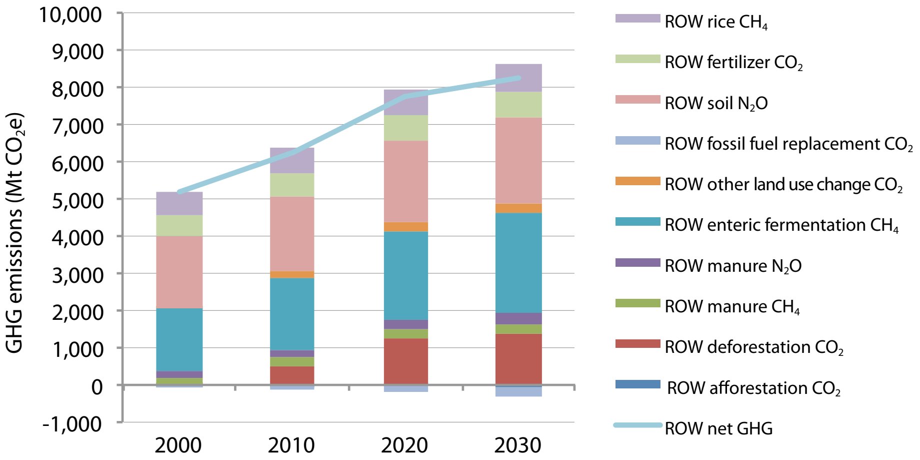
Total GHG emissions from agriculture and land use change remain relatively stable in the United States between 2010 and 2030, and as a result, net GHG emissions decrease over the period with the replacement of fossil fuels by biofuels (Figure 3). The additional carbon sinks due to establishment of short-rotation tree plantations (afforestation carbon sequestration) cancel out emissions from conversion of forests and grassland to developed land. Emissions from crop management tend to decrease over the period. However, emissions from livestock sector, including enteric fermentation CH_4, and manure CH_4 and N_2O, increase greatly (24.5% from 2010 to 2030).

Figure 3. Evolution of average annual GHG emissions from agriculture and land use change in the U.S.



In the rest of the world, the main source of additional emissions is deforestation. Other major sources include emissions from the livestock sector and crop management. Net GHG emissions from agriculture and land use change grow rapidly (30%) between 2010 and 2030 (Figure 4).

Figure 4. Evolution of average annual GHG emissions from agriculture and land use change in the ROW



Note: These emissions are directly linked to expansion of agricultural land, one cause of total deforestation. As deforestation is the primary source of agricultural expansion, deforestation CO_2 contributes greatly to total emissions in the rest of the world.

Policy analysis

The present analysis considered multiple levels of RFS2 targets and a biofuel mix different from that deviates from the RFS2 (Table A1). In two of the modeled scenarios, the RFS2 biofuel mandate is *decreased* by 25% increments (RFS2 75% and RFS2 50%) and in two others, the mandate is *increased* by 25% increments (RFS2 125% and RFS2 150%). These shocks are performed without changing the structure of the biofuel mix (thus, only the total volume of each mandated fuel is altered). In the RFS2 high corn scenario, the mandate level remains the same as that in RFS2, but corn ethanol fulfills 64% rather than 45% of the target, and the cellulosic ethanol share drops from 41% to 21%. This scenario captures the (very real) possibility that the future rising share of the mandate attributable to cellulosic ethanol cannot be achieved due to the slow advancement of commercially viable production. Indeed, provisions exist in the RFS2 that allows EPA to waive mandate components if they are deemed unachievable that year. This waiver has been exercised the last two years for cellulosic ethanol (Meyer and Thompson 2011). The results are presented in comparison with the baseline (RFS2).

Biofuels and biofuel feedstocks

The various biofuel targets lead to a proportional change in the feedstock demand for processing. The processed quantity of corn varies between 72 Mt and 217 Mt after 2020 (Table A2 in appendix). The processed quantity of soybeans in the United States varies between 15 Mt and 30 Mt, but an increase in the biofuel mandate above the baseline level as well as a higher share of corn ethanol (RFS2 high corn) leads to a decrease in the quantity of soybeans processed. This reduction is compensated by higher levels of rapeseed processing in the United States. The cellulosic biomass for second-generation biofuels comes, by model construction, from woody biomass. Biomass from short-rotation plantations, as compared with forest and forest industry residues, accounts for more than half of the total cellulosic feedstock demand in all scenarios.

Relative to the RFS2 baseline, U.S. corn production deviates -14% in the RFS2 50% scenario to +14% in the RFS2 150% scenario. However, the level of soybean production evolves in the direction opposite biofuel demand: in 2020, a 50% decrease in the biofuel mandate to an 11% increase in soybean production, and a 50% increase leads to a 7% decrease. One reason for this shift is the change in the availability of DDGS as a feed substitute in the livestock sector. Greater levels of corn ethanol lead to higher DDGS coproduction, thus reducing the conventional demand for soybeans in the feed market. On the second-generation side, production of wood from U.S. short-rotation plantations varies within a range of 3%, but most of the adjustment across scenarios is made through imports: in 2020, the total woody biomass production for bioenergy use varies between 296 and 313 million m^3, and woody biomass imports vary between 397 and 412 million m^3 across scenarios. Biomass imports grow to help meet the rising biofuel demand.

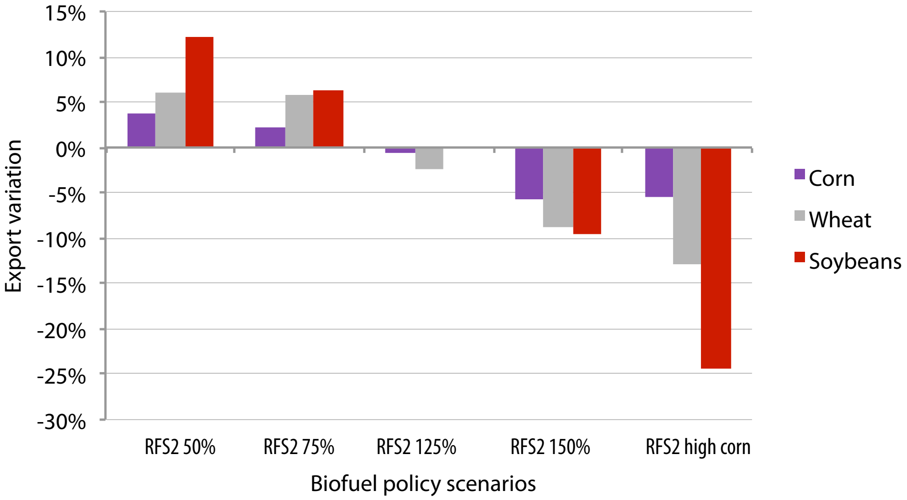
Market conditions

Prices tend to increase for crops used for biofuel production but decrease for by-products. However, increased replacement of traditional feed by biofuel by-products dampens these effects. The highest impact of biofuel policies on domestic prices is observed between 2010 and 2020. A 50% increase in the target leads to a 9% increase in the price of corn relative to that price in the baseline (Table A3 in appendix). Prices for all commodities tend to go up on the domestic market—especially for cotton (+22% in 2020), sorghum (+16%), and wheat (+8%)—as competition for land intensifies. Soybean prices are driven by increased processing demand and decreased production, which result in a +12% price increase when the biofuel target rises by 50%. However, the scenario with the strongest impact on domestic prices is RFS2 high corn: between 2010 and 2020, the price of corn increases by 11%; that of soybeans, by 14%; and that of wheat, by 12%. Between 2020 and 2030, stabilization of U.S. biofuel demand and a further increase in productivity reduce pressure on domestic agricultural markets, lowering prices and effectively ending the impact of biofuel policy.

With respect to the livestock sector, the impact of biofuel policy depends on the products used for animal feeding and their potential substitutes. In the present analysis, biofuel byproducts can be substitutes only for corn and soybeans; other feed ratios are fixed by region, species, and production system. Further adjustment is possible by switching one production system for another. Between 2010 and 2020, when the biofuel mandate increases, additional by-products are available, but because the prices of other crops increase, demand for by-products in the livestock sector also increase, leading to a slight rise in by-product prices. However, the livestock sector (the consumer in particular) benefits from higher biofuel targets: meat prices would increase 3% to 4% if the biofuel mandate were cut by half but would decrease from 1% to 3% if the mandate were raised by half (Table A4 in appendix). This differs from Baker et al. 2011, where higher mandates induced higher livestock and meat prices.

Increased domestic prices for crops alter the terms of trade of U.S. net exports: as the biofuel mandate rises, exports fall (Figure 5). Corn, soybean, and wheat net exports are strongly affected. More than half of the reduction of corn exports is distributed among Latin America (almost 30%); the Middle East, North Africa, and Sub-Saharan Africa (from 20% to 27%); and Japan (10%). U.S. net exports are even more affected in the high corn scenario. In the RFS2 50% scenario, increased U.S. corn exports would especially benefit Canada, Latin America, the Middle East, and North Africa. Australia, Europe, and Latin America would increase their market share to the detriment of U.S. interests when the biofuel mandate rises; the reduction in U.S. corn exports would not be fully compensated, mainly because of the impact of prices on world feed demand (from +5% to -7% across scenarios).

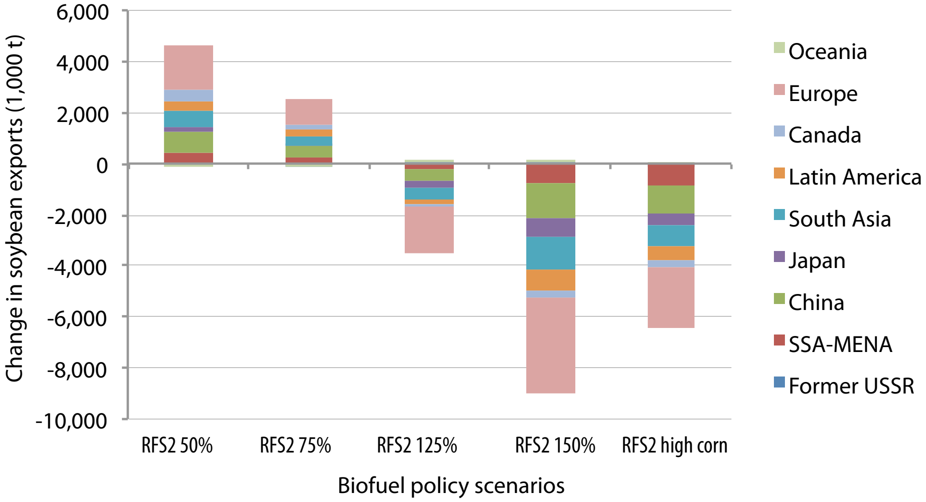
Figure 5. U.S. net exports in five biofuel policy scenarios relative to the RFS2 baseline in 2020



With respect to soybeans, the U.S. exports reduction mainly affects the Middle East and North Africa, Asia, and Europe (Figure 6). Soybean-importing regions adjust by reducing their demand for processing (Europe) and feed and food (China, South Korea, the Middle East and North Africa) and by increasing their domestic production. Latin American countries benefit from U.S. market share losses by increasing their exports. In 2020, global soybean exports are still 6% lower in the RFS2 150% scenario than in the baseline, but in 2030, Latin American exports almost fully compensate for the U.S. exports reduction (1% reduction of global soybean exports).

With respect to wheat, the reduction in U.S. exports mainly affects Central America. The market shares of Australia and New Zealand, South America, and the former USSR countries increase. The reduction in U.S. cotton exports is only partly compensated for by an increase of exports from Australia and Turkey. The demand for U.S. biofuels also indirectly affects Brazil's exports of cotton, due to the increase in demand for sugar cane and soybeans.

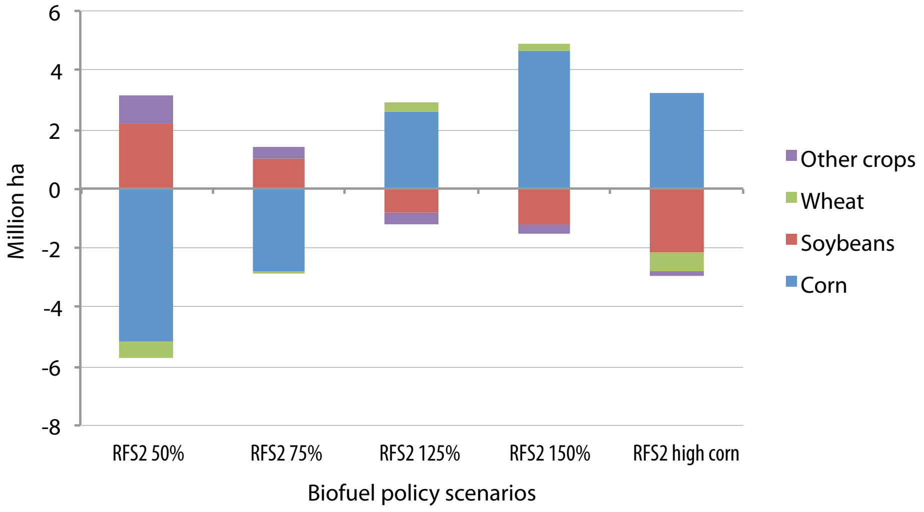
Figure 6. Absolute differences in soybean exports by destination relative to the RFS2 baseline in 2020



Land use

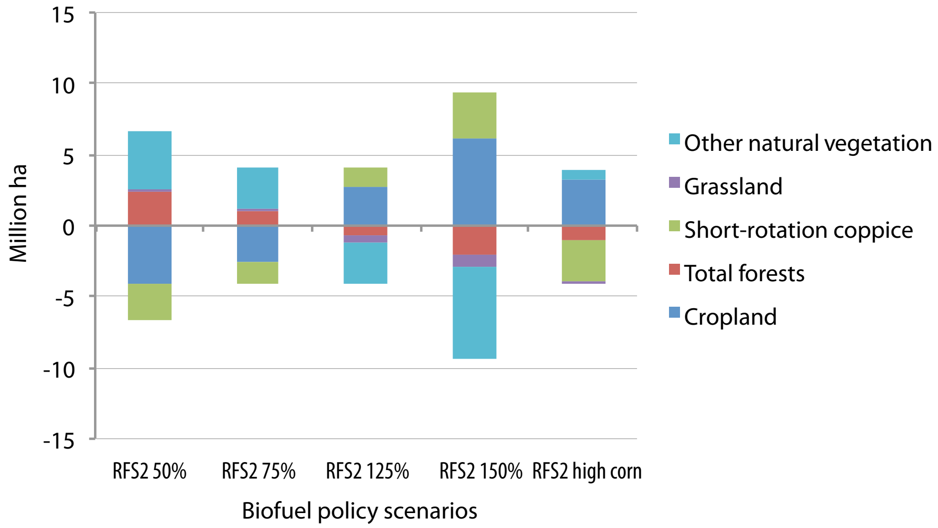
The most significant land use effects of the alternative biofuel policy scenarios is on U.S. corn acreage, which in 2020 varies from -14% to +14% or from -5.1 Mha to +4.6 Mha (Figure 7). The adjustment in this acreage is made through changes in the area planted with other U.S. crops and through total cropland area. The competition for land is especially strong between corn and soybeans, which are largely grown in the same areas. Adjustment in soybean area is responsible for 26% to 67% of the total corn area variation, depending on the policy scenario; The "RFS2 high corn" scenario reduces soybean area by 2.2 Mha. Cotton and sorghum area adjustment accounts for 4% and 8%, respectively, of the total corn area variation. Higher biofuel targets also lead to reductions, although smaller, in other crop areas. The rest of the corn area variation is accommodated through other types of land conversion; grasslands and other natural land areas decrease when the biofuel mandate increases. All of these adjustments lead to a variation in the total U.S. cropland area ranging from -1.5 Mha to +2.4 Mha from the RFS2 baseline across scenarios. Of note, productivity increases reduce the additional area required to grow extra corn; this additional area is lowered to 3.1 Mha (from 4.6 Mha, above) in the RFS2 150% scenario in 2030. The impact of biofuel policies is only slightly smaller in terms of total cropland area change than productivity gains per unit area but larger in relative terms, because total cropland area decreases between 2020 and 2030.

Figure 7. Absolute area change by crop relative to the RFS2 baseline in 2020 in the U.S.



The change in second-generation biofuel demand leads to a variation in the area of short-rotation tree plantations of between -1.2% and +2.5% relative to the RFS2 baseline across scenarios. Expansion of these plantations and of cropland in the United States and elsewhere leads to decrease of grassland (+0.2 Mha to -0.6 Mha in 2030) and other natural land areas, including idle cropland, (+1.42 Mha to -1.8 Mha) in the rest of the world. A higher U.S. biofuel mandate also increases cropland and short-rotation tree plantation area at the expense of other natural land and forests in the rest of the world (Figure 8). In 2020, the total additional land required outside the United States to fulfill a 50% biofuel mandate increase is almost 10 Mha.

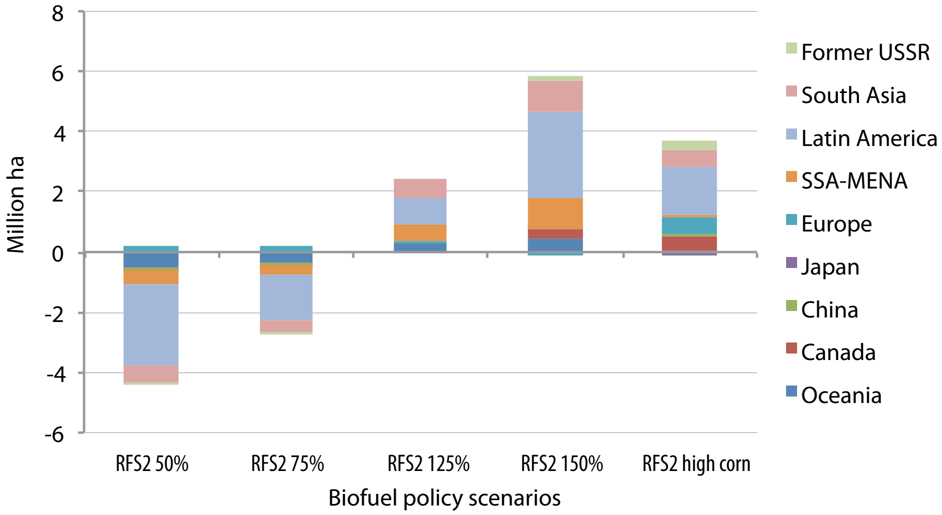
Figure 8. Absolute area change by land type relative to the RFS2 baseline in 2020 outside the U.S.



Cropland expansion occurs mainly in Latin American countries (Figure 9). Under increased biofuel targets, Brazil exports more sugarcane ethanol to the United States; more generally, Latin American countries increase their soybean and wheat production to compensate for the U.S. exports reduction. The second largest adjustment in cropland area across scenarios occurs in Africa and is driven by the expansion of corn, oilseeds, and wheat area in sub-Saharan Africa and by the expansion of barley and sugarcane in the Middle East and North Africa. Cropland area appears to be less affected in Asia. However, this result masks underlying changes within the region: increased biofuel targets trigger a decrease in cropland area in China and an increase in cropland area in Southeast Asia and Japan. Other developed countries and the former USSR countries also experience some, albeit smaller, cropland adjustment, with one exception:

under the high corn scenario, Australia, Canada, European countries, and former USSR countries experience significant cereal expansion, leading to a maximum cropland increase of 1.4 Mha relative to the baseline.

Figure 9. Regional cropland variation relative to the baseline outside U.S. in 2020

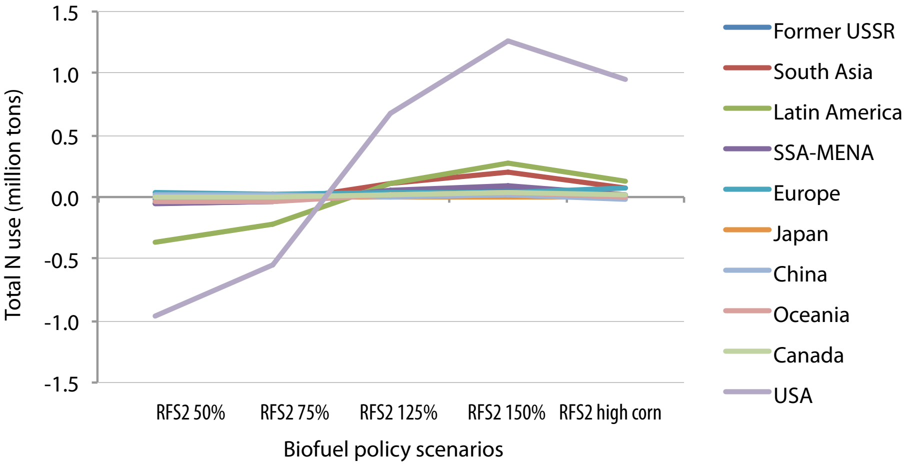


Nitrogen use and intensity

Increased demand for biofuels not only drives land use change but also significantly increases fertilizer use, raising additional environmental concerns. In the United States, total nitrogen use increases with the mandate. The absolute change in U.S. nitrogen use in 2020 ranges from -0.96 to +1.26 million nutrient tons, or -7.9% to +10.4% relative to the baseline. Higher mandates also increase the average nitrogen use intensity per hectare of cropland, which ranges from -4.3% to +%7.2 across scenarios. The higher nitrogen use intensity results from a shift to more intensive management systems and replacement of soybeans (a low nitrogen user) by corn and other high nitrogen input crops. In general, nitrogen use and intensity are more sensitive to biofuel scenarios in the present analysis than suggested by estimates from Baker et al. (2011). Baker et al. show that changes in nitrogen use would range from -2.1% to +2.5% for a 25% decrease and a 25% increase, respectively, in the volume of the mandate, whereas this analysis indicates U.S. nitrogen use changes ranging from -4.4% to 5.6%. The primary reason for this difference is that in response to increased mandates, soybean area actually decreases according to this study but increases in Baker et al. 2011—thereby muting the net effect on total nitrogen use.

Outside the United States, this analysis also projects an increase in nitrogen use. Nitrogen intensity per hectare of cropland increases greatly in South America and to a lower extent in sub-Saharan Africa and South Asia. Nitrogen consumption increases in most of the rest of the world as well (Figure 10). In 2020, the RFS2 150% scenario requires the additional use of 9.6 Mt of nitrogen globally relative to the baseline. This shift is approximately a 10% increase over 2020 RFS2 baseline levels. The largest non-U.S. shifts in nitrogen use occur in Latin America.

Figure 10. Regional change in nitrogen use under various biofuel policies relative to the baseline in 2020



GHG emissions

Land conversion and synthetic fertilizer use are significant sources of GHG emissions. Therefore, the greater the increase in the U.S. biofuel mandate, the higher the GHG emissions from land use change and agriculture, both in the United States and abroad (Table 3). Fertilizer use, especially nitrogen use, is the main source of additional GHG emissions (N_2O) in the United States. The net change in GHG emissions from biofuel expansion-induced land use change in the United States is essentially zero. On the one hand, CO_2 sinks increase due to expansion of forest, but cropland expansion increases emissions. The end result is no discernible change in emissions overall. In general, increasing biofuel use in the United States would appear to be beneficial to domestic GHG emissions reduction, because emissions displacement due to fossil fuel replacement more than offset the emissions increase in agriculture, a finding supported by Baker et al. (2011) and others. However, this result can change if the share of corn ethanol fulfilling the biofuel mandate is increased: GHG emissions are 2.4% higher in the RFS2 high corn scenario than in the baseline.

The critical finding here, however, comes from the net global effects of U.S. biofuel policies. The results indicate these policies create additional GHG emissions in the rest of the world. In the RFS2 150% scenario, GHG emissions outside the United States increase by 0.7% relative to the baseline, because of emissions from land use change and fertilizer use. The overall effect is a *net global increase in GHG emissions for all scenarios in which the United States increases its mandates for biofuels*. Moreover, a biofuel mandate with a high share of corn ethanol would lead to additional GHG emissions. Here, the GHG displacement potential of biofuels is lower when cellulosic ethanol requirements are shifted to corn-based ethanol requirements, and emissions from LUC and nitrogen fertilizer use are not balanced out by increased carbon sequestration. Achieving the RFS2 mandate with a 66% instead of 45% share of corn ethanol in the United States would add 27 million tons of CO_2 to the atmosphere every year over the 2010–2030 period.

Table 3. Annualized GHG emissions by source for different U.S. biofuel targets (in Mt CO_2e)

Source of GHG emissions	RFS2 50%	RFS2 75%	RFS2 100%	RFS2 125%	RFS2 150%	RFS2 high corn
United States						
Afforestation	-23	-23	-23	-24	-24	-23
Deforestation	33	34	34	33	34	33
Other LUC	3	4	5	5	7	6
Total LUC	**14**	**14**	**16**	**15**	**17**	**16**
Crop production	302	315	328	345	358	338
Livestock production	225	225	226	226	226	226
Total agriculture	**527**	**540**	**554**	**571**	**584**	**564**
Fossil fuel displacement	**-59**	**-88**	**-120**	**-153**	**-185**	**-119**
Total	**482**	**467**	**450**	**434**	**416**	**461**
Rest of the World						
Afforestation	-21	-21	-20	-19	-20	-20
Deforestation	920	931	935	943	957	942
Other LUC	223	225	230	236	243	233
Total LUC	**1,122**	**1,135**	**1,145**	**1,160**	**1,180**	**1,156**
Crop production	3,477	3,484	3,496	3,510	3,520	3,501
Livestock production	2,697	2,698	2,694	2,695	2,694	2,695
Total agriculture	**6,174**	**6,182**	**6,190**	**6,205**	**6,214**	**6,196**
Fossil fuel displacement	**-162**	**-165**	**-167**	**-169**	**-171**	**-167**
Total	**7,134**	**7,151**	**7,169**	**7,196**	**7,223**	**7,185**
World						
Afforestation	-44	-44	-44	-42	-43	-44
Deforestation	953	964	969	976	991	976
Other LUC	226	229	235	242	250	239
Total LUC	**1,136**	**1,149**	**1,161**	**1,176**	**1,197**	**1,172**
Crop production	3,780	3,799	3,824	3,855	3,879	3,840
Livestock production	2,923	2,923	2,920	2,921	2,920	2,921
Total agriculture	**6,703**	**6,722**	**6,744**	**6,776**	**6,799**	**6,761**
Fossil fuel displacement	**-221**	**-253**	**-286**	**-322**	**-356**	**-286**
Total	**7,617**	**7,618**	**7,619**	**7,629**	**7,639**	**7,646**

Note: Emissions are computed as an annualized GHG flow over 2010 and 2030 using a 4% discount rate.

To compare GHG emissions changes associated with biofuel policy with direct emissions savings, this study calculates the ILUC factor associated with that policy. It does so by dividing the additional emissions from land use change relative to the RFS2 50% scenario over the 2010–2030 period by the length of the period (30 years) and the volume of additional U.S. biofuel consumption at the pinnacle of RFS2. The resulting ILUC factor associated with the U.S. biofuel policy varies between 20 and 29 g CO_2 per MJ depending on the marginal increment and growth rate assumption considered (Table 4). For now, consider the "Base yield growth" result. The other scenarios will be discussed below in the productivity growth sensitivity analysis section. This base growth ILUC factor accords with the EPA (2010) estimates of 30 g CO_2 per MJ for corn ethanol, 40 g CO_2 per MJ for soybean biodiesel, 14 g CO_2 per MJ for switchgrass, and 4 g CO_2 per MJ for sugarcane ethanol. If the weights of these different feedstocks to fulfill the mandate in the model are considered,[5] the average ILUC factor based on would be approximately 21 g CO_2 for RFS2. This factor is slightly lower than the estimate from Hertel et al. (2010): 27 g CO_2 per MJ.

Table 4. ILUC factor across scenarios and for varying crop yield-growth assumptions, 2010–2030

	Units	RFS2 75%	RFS2 100%	RFS2 125%	RFS2 150%	RFS2 high corn
Biofuel difference*	1,000 GJ	621,143	1,242,286	1,863,430	2,484,573	1,242,286
Base yield growth						
LUC total GHG difference*	Mt CO_2e	390	750	1,200	1,830	1,080
ILUC GHG factor	g CO_2e/MJ	21	20	21	25	29
0.5 yield growth						
LUC total GHG difference*	Mt CO_2e	514	953	1,572	2,404	1,209
ILUC GHG factor	g CO_2e/MJ	28	26	28	32	32
0.2 yield growth						
LUC total GHG difference*	Mt CO_2e	488	1,089	1,949	3234	1,721
ILUC GHG factor	g CO_2e/MJ	26	29	35	43	46

* Differences are computed relative to the RFS2 50% scenario. Total GHG emissions from land use change are computed with a 4% discount rate.

Sensitivity analysis

Future productivity growth in agriculture is one of the most important but uncertain factors in this analysis. The growth in crop yield observed in the past may not be continued in the future because of climate change (Nelson et al. 2010) or soil and water depletion in some productive regions (Rosegrant et al. 2002). The capacity of developed countries to pursue technological innovation at the pace observed in the last several decades is also questionable. This analysis' baseline assumption is that the United States will continue to attain the annual crop-yield growth that it has achieved since at least 1990 and that the rest of the world will experience a 1% exogenous growth increase (hereafter, base yield growth). However, it also tests the sensitivity of its policy simulation results to potentially lower exogenous yield growth. Accordingly, the RFS2 baseline is run for two additional scenarios with respect to alternative exogenous yield growth rates for the rest of the world: 50% lower exogenous yield growth (the 0.5 Yield Growth scenario) and 80% lower exogenous yield growth (the 0.2 Yield Growth scenario).

Lower crop yields in the future would lead to lower production and hence higher agricultural commodity prices. For instance, in 2020 under the RFS2 (baseline) scenario, the average world corn price is 37% higher when the annual crop-yield growth is limited to 0.5% instead of 1% and is twice as high when that growth is limited to 0.2%. The effects on soybean and wheat prices are even stronger (Table A5 in appendix). Consequently, demand is reduced and production slows (Figure A1 in appendix). Lower yield growth leads to a much higher expansion of cropland (Figure 11) than baseline yield growth, and this expansion occurs at the expense of forests. In 2030, 26 Mha and 42 Mha of forest loss and 55 Mha and 102 Mha of other natural land loss are associated with 0.5% and 0.2% annual yield growth, respectively. In 2030, U.S. cropland area is 8 Mha larger under a 0.5% yield growth assumption and 15 Mha larger with a 0.2% yield growth assumption. Under the RFS2, emissions from land use change are 50% and 112% higher in the United States, and 30% and 50% higher in the rest of the world with 50% lower yield growth and 80% lower yield growth, respectively (Table A6 in appendix).

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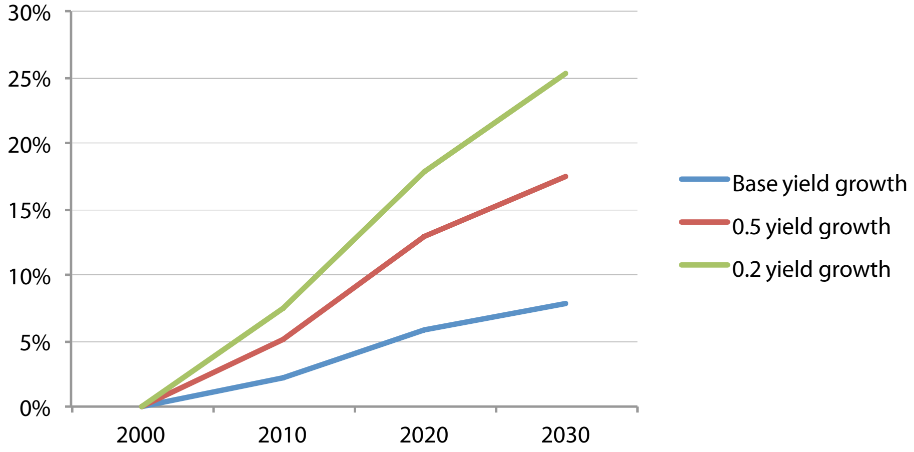
[5] The ILUC factor for switchgrass is applied to short-rotation coppice.

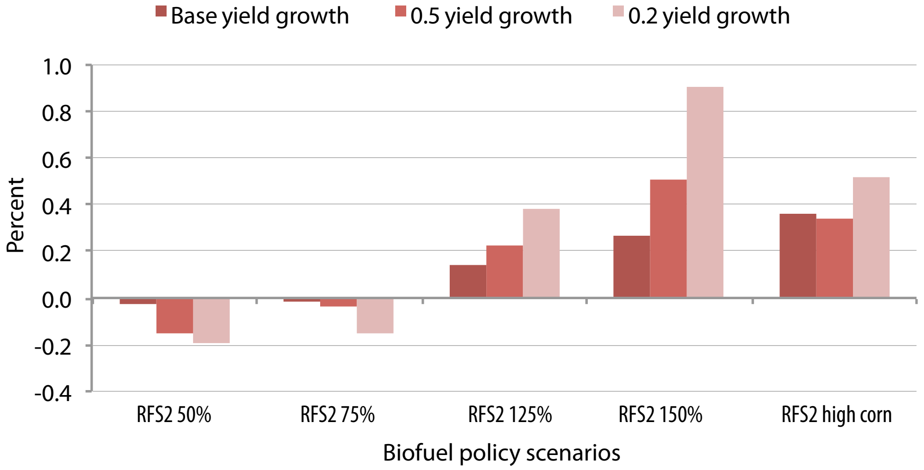
Figure 11. Evolution of global cropland area under various crop productivity assumptions in the RFS2 scenario



Another important consequence of a lower yield growth in the future is reallocation of agricultural production, specifically, a reduction in reliance on domestic production and an increase in food imports by less productive areas from more productive areas (Figure A2 in appendix). In fact, lower yield growth reinforces allocation of agricultural production according to the comparative advantage of each region and increases traded quantities. Consequently, dependence on food imports grows.

In terms of GHG emissions, trends projected under the Base Yield Growth scenario hold: an increase in the biofuel mandate would reduce U.S. emissions but would increase GHG emissions in the rest of the world. The net effect is an increase in global GHG emissions with higher biofuel targets (Table A6 in appendix). However, because lower yield growth expands the U.S. role in the international cereal market and because possibilities to expand production on existing cropland are limited worldwide, decreased productivity growth magnifies the negative impacts of U.S. biofuel policies on international GHG emissions from agriculture and land use change (Figure 12). A 50% increase in the mandate relative to the baseline leads to a net rise in global GHG emissions from agriculture and land use that varies between 0.3% and 0.9%. Moreover, if more than 90% of the additional GHG emissions in the rest of the world are offset by U.S. savings in the RFS2 base productivity scenario, only 73% and 68% of those emissions would be offset when exogenous yield growth is 50% and 80% lower, respectively. In the RFS2 high corn scenario, the U.S. savings offset 42% of additional emissions in the rest of the world, given the baseline productivity assumption, but offset only 36% and 28% of emissions with 50% and 80% lower yield growth, respectively (Table A7 in appendix).

Figure 12. Sensitivity of global annualized GHG emissions to varying assumptions about exogenous productivity growth relative to RFS2 baseline



Note: GHG emissions are computed as an average annuity over the 2010–2030 period with a 4% discount rate.

All sources of emissions (crops, livestock, and land use) are sensitive to the assumption about exogenous productivity growth, but emissions from land use change are the most sensitive. When exogenous productivity growth is limited to 0.2% per year, land use change becomes the principal source of additional GHG emissions due to biofuel policy (Figure A3 in appendix).

Consider the ILUC emissions factors for the RFS2 baseline (100%) introduced in Table 4 above. The ILUC factor increases to 26 g CO_2 per MJ under the 0.5 Yield Growth scenario and to 29 g CO_2 per MJ under the RFS2 0.2 Yield Growth scenario. The highest ILUC factor remains associated with the RFS2 high corn scenario, and that factor rises to 46 g CO_2 per MJ in the worst yield growth scenario (Table A4 in appendix). Lower exogenous productivity growth will also considerably increase emissions from the livestock sector. When exogenous productivity growth is only 0.2% per year, total emissions from livestock increase 0.6% relative to the baseline of 1% growth (Figure A3 in appendix). Increases in cereal prices decrease the competitiveness of mixed crop-livestock systems compared with grass-based systems. Because cattle productivity is much lower in grass-based systems than in mixed systems, the former require more animals to produce a given amount of meat than the latter and therefore increase emissions from the livestock sector globally.

Conclusion

The potential climate change mitigation benefits of biofuels are at the center of an intense controversy in several regions of the world where bioenergy receives significant public support. The present analysis considered the global impact of the U.S. Renewable Fuel Standard (RFS2) program over the 2010–2030 horizon as well as the impact of volumetric shifts in the policy-mandated biofuel portfolio, including crop ethanol, biodiesel, and cellulosic ethanol. Departing from both the top-down modeling that provides broad coverage and little depth and bottom-up modeling that provides depth but not broad coverage, this analysis used a global economic model based on a detailed representation of land use and agricultural production possibilities at the grid-cell level. Although all feedstock combinations could not be explored, the analysis clearly delineates the role of trade in shifting agricultural activity and producing emissions leakage. Indeed, the global and multisectoral characteristics of the model used in the analysis make it possible to track emissions shifting through land use reallocations and the movement of a given land use from one region to another through trade flow variations, while accounting for production intensification through changes in management practices.

The analysis shows that the overall effect of U.S. biofuel policy depends on the balance between the reduction in U.S. emissions from fossil fuel displacement through increased U.S. biofuel production and the generation of additional emissions in the rest of the world. If the mandate level is reduced below what is called for by RFS2 (50% or 75% of the current mandate), this causes emissions outside the United States to reduce proportionally with the increase in U.S. emissions, the latter of which includes forgone reductions in emissions from displaced fossil fuels such as gasoline. Under such a scenario, the net change in global GHG emissions is essentially zero from changing the U.S. mandate. However, raising the current RFS2 mandate (125% or 150% of the current mandate) leads to growth in emissions outside the United States—growth that exceeds reductions in U.S. fossil fuel emissions, leading to a net increase in emissions globally. A mandate with the same volumetric requirements as the RFS2 mandate, but with a high corn ethanol share, will increase global emissions as well (by 30 Mt CO_2e relative to RFS2).

Estimates of ILUC magnitude in this analysis are within the range of others in the literature. The 30-year ILUC factor for the RFS2 target is 20 g CO_2 per MJ if corn ethanol is limited to 34% of the biofuel target and 29 g CO_2 per MJ if the share of corn ethanol increases to 66% of the target—figures in line with EPA calculations. However, estimates of emissions associated with fertilizer use for intensified production are higher than those presented by EPA and partly explain the difference in the final balance. These results are obtained under possibly optimistic assumptions about yield growth in different regions of the world. As illustrated by the sensitivity analysis presented here, lower productivity growth would exacerbate pressure on land, leading to higher impacts of biofuel policies on global agriculture and land use. With exogenous yield growth limited to 0.2% per year, increased emissions resulting from cropland expansion would raise the ILUC factor of the RFS2 target to 29 g CO_2 per MJ if the share of corn ethanol was increased to 45% of the biofuel target and to 46 g CO_2 per MJ if that share was increased to 64% of the target. An increase in the corn ethanol share would boost ILUC emissions, undercutting the fossil fuel displacement benefits of biofuels. Moreover, the concern that biofuels could compete with food production appears to be supported by higher food prices and a larger dependence on food imports by several developing countries.

This analysis models the impacts of regional policies on the rest of the world through the international trade channel. Harmonizing the scenarios and modeling assumptions of GLOBIOM with those of the U.S. FASOMGHG model allowed for an improved representation of U.S. agricultural markets in the global framework. Nevertheless, this assessment faces some challenges and limitations that suggest research tracks for the future.

The first limitation of the analysis is the number of biofuel products considered. In particular, the analysis assumed that short-rotation coppice and sawmills' wood residues would be the most used feedstock for second-generation biofuels. But other biofuel alternatives such as crop residues and perennial grasses (miscanthus or switchgrass) are viable alternatives not currently included in the GLOBIOM model. Crop residues do not require additional land use change and are already available; however, the impact of crop residues removal on crop yield could be significant due to a reduction in soil nutrients (Schnepf 2010). Pilot projects have shown that energy yield would be higher with perennial grasses than with short-rotation coppice, potentially reducing the acreage required to fulfill the second-generation biofuel mandate. Additionally, the analysis considers only a single representative production pathway for each of the crops studied, whereas in reality many alternative pathways exist for producing biofuels, each offering different GHG displacement potential based on varied technical specifications for refineries.

The second limitation of the analysis is that the impact of biofuel policy on the livestock sector remains difficult to determine, because a mandate increases the availability of biofuel by-products that can be used for animal feeding and increases prices of other feedstocks. Until recently, the aggregated effects of such feed composition changes were difficult to understand, but better estimates of substitution ratios and incorporation ranges can be now be found by type of animal (Hoffman and Baker 2011) and, along with harmonization of GLOBIOM and FASOMGHG, should improve description of these effects.

The third limitation of the analysis is related to the crucial role of yield for the net efficiency of biofuel policy. We demonstrate this via sensitivity analysis on broad scale productivity parameters, but more refined region-specific assumptions about yield are needed. In particular, improved understanding of production intensification responses to price shifts, particularly as it relates to synthetic fertilizer use to improve yields, is a key question that deserves further investigation. Incorporation of climate change feedbacks would also be useful for understanding the interaction between yield issues and biofuel impact on future agricultural markets.

Enhancing agricultural productivity in the United States and the rest of the world should be the condition for further development of biofuels. This analysis indicates that biofuel mandates based on second-generation biofuels could increase land pressures and actually increase net global GHG emissions. The availability and suitability of marginal land for growing biofuel feedstock is still under debate, and the economic profitability of production on such land could be challenging. More flexible programs favoring investments in agricultural research and technological diffusion across countries should therefore be encouraged before mandatory biofuel targets are imposed. The focus should be on technologies that increase efficiency and allow substitution of natural fertilizers for synthetic fertilizers while fostering development of the rural poor in developing countries.

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Appendix

GLOBIOM represents 28 regions, but this analysis regroups the countries of these regions into 10 regions.

GLOBIOM's 28 regions:

ANZ: *Australia*, *New Zealand*; **Brazil**; **Canada**; **China**; **Congo Basin**: *Cameroon*, *Central African Republic*, *Congo Republic*, *Democratic Republic of Congo*, *Equatorial Guinea*, *Gabon*; **EU Baltic**: *Estonia*, *Latvia*, *Lithuania*; **EU Central East**: *Bulgaria*, *Czech Republic*, *Hungary*, *Poland*, *Romania*, *Slovakia*, *Slovenia*; **EU Mid West**: *Austria*, *Belgium*, *Germany*, *France*, *Luxembourg*, *Netherlands*; **EU North**: *Denmark*, *Finland*, *Ireland*, *Sweden*, *United Kingdom*; **EU South**: *Cyprus*, *Greece*, *Italy*, *Malta*, *Portugal*, *Spain*; **Former USSR**: *Armenia*, *Azerbaijan*, *Belarus*, *Georgia*, *Kazakhstan*, *Kyrgyzstan*, *Moldova*, *Russian Federation*, *Tajikistan*, *Turkmenistan*, *Ukraine*, *Uzbekistan*; **India**; **Japan**; **Mexico**; **Middle East and North Africa (MENA)**: *Algeria*, *Bahrain*, *Egypt*, *Iran*, *Iraq*, *Israel*, *Jordan*, *Kuwait*, *Lebanon*, *Libya*, *Morocco*, *Oman*, *Qatar*, *Saudi Arabia*, *Syria*, *Tunisia*, *United Arab Emirates*, *Yemen*; **Pacific Islands**: *Fiji Islands*, *Kiribati*, *Papua New Guinea*, *Samoa*, *Solomon Islands*, *Tonga*, *Vanuatu*; **RCAM**: *Bahamas*, *Barbados*, *Belize*, *Bermuda*, *Costa Rica*, *Cuba*, *Dominica*, *Dominican Republic*, *El Salvador*, *Grenada*, *Guatemala*, *Haiti*, *Honduras*, *Jamaica*, *Nicaragua*, *Netherland Antilles*, *Panama*, *St Lucia*, *St Vincent*, *Trinidad and Tobago*; **RCEU**: *Albania*, *Bosnia and Herzegovina*, *Croatia*, *Macedonia*, *Serbia-Montenegro*; **ROWE**: *Gibraltar*, *Iceland*, *Norway*, *Switzerland*; **RSAM**: *Argentina*, *Bolivia*, *Chile*, *Colombia*, *Ecuador*, *Guyana*, *Paraguay*, *Peru*, *Suriname*, *Uruguay*, *Venezuela*; **RSAS**: *Afghanistan*, *Bangladesh*, *Bhutan*, *Maldives*, *Nepal*, *Pakistan*, *Sri Lanka*; **RSEA OPA**: *Brunei Daressalaam*, *Indonesia*, *Singapore*, *Malaysia*, *Myanmar*, *Philippines*, *Thailand*; **RSEA PAC**: *Cambodia*, *Korea DPR*, *Laos*, *Mongolia*, *Viet Nam*; **South Africa**; **South Korea**; **Sub Saharan Africa (SSA)**: *Angola*, *Benin*, *Botswana*, *Burkina Faso*, *Burundi*, *Cape Verde*, *Chad*, *Comoros*, *Cote d'Ivoire*, *Djibouti*, *Eritrea*, *Ethiopia*, *Gambia*, *Ghana*, *Guinea*, *Guinea Bissau*, *Kenya*, *Lesotho*, *Liberia*, *Madagascar*, *Malawi*, *Mali*, *Martinique*, *Mauritania*, *Mozambique*, *Niger*, *Nigeria*, *Rwanda*, *Sao Tome Principe*, *Senegal*, *Seychelles*, *Sierra Leone*, *Somalia*, *Sudan*, *Swaziland*, *Tanzania*, *Togo*, *Uganda*, *Zambia*, *Zimbabwe*; **Turkey**; **United States of America (USA)**.

Ten regions in the analysis: Results output: 10 aggregated regions:

United States, **Oceania**: *ANZ*, *Pacific Islands*; **Europe**: *EU Baltic*, *EU Central East*, *EU Mid West*, *EU South*, *EU North*, *RCEU*, *ROWE*, *Turkey*; **Former USSR**; **Latin America**: *Brazil*, *Mexico*, *RCAM*, *RSAM*; **Sub-Saharan Africa and MENA**: *Congo Basin*, *SSA*, *South Africa*, *MENA*; **Canada**; **Japan**, **China**, **South Asia**: *India*, *RSEA OPA*, *RSEA PAC*, *South Korea*, *RSAS*.

Table A1. Level and composition of the U.S. biofuel consumption target in EJ

		2010	2020	2030
Total biofuels	RFS2 50%	0.59	1.38	1.38
	RFS2 75%	0.89	2.07	2.07
	RFS2 baseline	1.19	2.76	2.76
	RFS2 125%	1.48	3.45	3.45
	RFS2 150%	1.78	4.14	4.14
	RFS2 high corn	1.19	2.76	2.76
Corn ethanol	Other scenarios	90%	45%	45%
	RFS2 high corn	90%	64%	64%
Sugarcane ethanol imports	Other scenarios	10%	10%	10%
	RFS2 high corn	10%	10%	10%
Cellulosic ethanol	Other scenarios	41%	41%	41%
	RFS2 high corn	3%	22%	22%

Table A2. Processed feedstock for U.S. biofuel production under varying levels of biofuel targets (crops in million tons, woody biomass in million m^3)

		2010	2020	2030
Corn	RFS2 50%	61.9	72.4	72.4
	RFS2 75%	92.9	108.6	108.6
	RFS2 baseline	123.8	144.8	144.8
	RFS2 125%	154.8	181	181
	RFS2 150%	185.7	217.2	217.2
	RFS2 high corn	123.8	207.7	207.7
Rapeseed	RFS2 baseline		2.1	1.7
	RFS2 125%	3	5.4	6.7
	RFS2 150%	3.7	6.1	12.2
	RFS2 high corn		2.7	6.2
Soybeans	RFS2 50%	8.9	15.3	15.3
	RFS2 75%	13.4	22.9	22.9
	RFS2 baseline	17.9	25.3	26.1
	RFS2 125%	14.9	24.6	21.3
	RFS2 150%	17.5	30.3	14.8
	RFS2 high corn	17.9	23.7	14.7
Woody biomass	RFS2 50%	7.9	240	240
	RFS2 75%	11.9	355.4	359.6
	RFS2 baseline	15.9	430	479.3
	RFS2 125%	19.8	504.6	573.1
	RFS2 150%	23.8	579.2	647.7
	RFS2 high corn	15.9	251.2	251.1

Table A3. Relative changes in prices of U.S. crops relative to the RFS2 baseline

	RFS2 50%	RFS2 75%	RFS2 125%	RFS2 150%	RFS2 high corn
		2010			
Corn	-7%	-4%	5%	13%	0%
Soybean	-8%	-5%	6%	18%	0%
Sorghum	-11%	-6%	8%	19%	0%
Wheat	-6%	-4%	6%	15%	0%
		2020			
Corn	-7%	-5%	3%	9%	11%
Soybean	-9%	-6%	5%	12%	14%
Sorghum	-12%	-9%	6%	16%	18%
Wheat	-4%	-5%	4%	8%	12%
		2030			
Corn	-1%	1%	0%	0%	0%
Soybean	1%	1%	0%	-2%	-2%
Sorghum	2%	2%	0%	-3%	0%
Wheat	0%	1%	-1%	0%	-1%

Table A4. Relative changes in prices of U.S. livestock commodities relative to the RFS2 baseline

	RFS2 50%	RFS2 75%	RFS2 125%	RFS2 150%	RFS2 high corn
		2010			
Cattle meat	0%	0%	0%	1%	0%
Ovine meat	-1%	-1%	8%	10%	0%
Pig meat	-1%	1%	-1%	4%	0%
Poultry meat	0%	1%	-2%	2%	0%
Milk	1%	2%	-3%	-2%	0%
Eggs	3%	5%	-8%	-5%	0%
		2020			
Cattle meat	2%	2%	1%	1%	1%
Ovine meat	0%	0%	1%	2%	0%
Pig meat	3%	6%	3%	7%	7%
Poultry meat	5%	6%	2%	4%	5%
Milk	0%	0%	0%	-3%	0%
Eggs	17%	18%	2%	5%	6%
		2030			
Cattle meat	3%	3%	0%	-1%	-1%
Ovine meat	0%	0%	0%	0%	0%
Pig meat	4%	5%	0%	-3%	-3%
Poultry meat	4%	4%	-1%	-3%	-3%
Milk	3%	3%	2%	4%	2%
Eggs	8%	8%	-1%	-7%	-7%

Table A5. Comparison of world price increases under varying yield growth assumptions relative to RFS2 baseline yield growth

	2010		2020		2030	
	0.5 yield growth	0.2 yield growth	0.5 yield growth	0.2 yield growth	0.5 yield growth	0.2 yield growth
Corn	18%	40%	37%	99%	29%	78%
Soybeans	24%	57%	60%	161%	45%	126%
Sorghum	52%	96%	59%	130%	46%	102%
Sugarcane	18%	40%	51%	122%	24%	87%
Sunflower	31%	68%	59%	190%	28%	113%
Sweet potatoes	7%	12%	11%	23%	10%	23%
Wheat	22%	45%	41%	110%	34%	86%
Cattle meat	7%	12%	12%	30%	10%	22%
Ovine meat	6%	11%	6%	18%	4%	12%
Pig meat	10%	21%	19%	48%	16%	37%
Poultry meat	8%	16%	16%	40%	13%	31%
Cow milk	1%	2%	2%	4%	1%	8%
Ovine meat	0%	1%	2%	3%	0%	2%
Eggs	7%	13%	14%	33%	12%	27%

Table A6. Average annual GHG emissions by source under varying U.S. biofuel targets and yield growth assumptions (in Mt CO_2e, computed as an average annuity over the 2010–2030 period with a 4% discount rate)

Source of GHG emissions	Assumption on yield growth	Scenario			
		RFS2 50%	RFS2 Baseline	RFS2 150%	RFS2 high corn
United States					
Total LUC	Base yield growth	14	16	17	16
	0.5 yield growth	23	24	27	24
	0.2 yield growth	33	34	34	35
Total agriculture	Base yield growth	527	554	584	564
	0.5 yield growth	584	610	640	620
	0.2 yield growth	611	635	660	646
Fossil fuel displacement	Base yield growth	-59	-120	-185	-119
	0.5 yield growth	-59	-120	-185	-119
	0.2 yield growth	-59	-120	-186	-120
Total	Base yield growth	482	450	416	461
	0.5 yield growth	548	515	481	526
	0.2 yield growth	586	549	507	561
Rest of the world					
Total LUC	Base yield growth	1122	1145	1180	1156
	0.5 yield growth	1473	1503	1549	1511
	0.2 yield growth	1729	1765	1836	1784
Total agriculture	Base yield growth	6175	6191	6214	6196
	0.5 yield growth	6363	6383	6417	6393
	0.2 yield growth	6521	6543	6597	6556

Source of GHG emissions	Assumption on yield growth	Scenario			
		RFS2 50%	RFS2 Baseline	RFS2 150%	RFS2 high corn
Fossil fuel displacement	Base yield growth	-162	-167	-171	-167
	0. yield growth	-161	-166	-171	-167
	0.2 yield growth	-162	-166	-170	-166
Total	Base yield growth	7134	7169	7223	7185
	0.5 yield growth	7675	7720	7795	7738
	0.2 yield growth	8088	8142	8263	8175
World					
Total LUC	Base yield growth	1136	1161	1197	1172
	0.5 yield growth	1495	1527	1576	1536
	0.2 yield growth	1762	1799	1870	1820
Total agriculture	Base yield growth	6702	6745	6798	6761
	0.5 yield growth	6947	6993	7057	7013
	0.2 yield growth	7132	7178	7257	7202
Fossil fuel displacement	Base yield growth	-221	-286	-356	-286
	0.5 yield growth	-220	-285	-356	-286
	0.2 yield growth	-221	-286	-357	-285
Total	Base yield growth	7617	7619	7639	7646
	0.5 yield growth	8223	8235	8276	8263
	0.2 yield growth	8674	8691	8770	8736

Table A7. Difference in total average annual GHG emissions relative to the RFS2 50% scenario under varying yield growth assumptions in the U.S. and in the ROW (in Mt CO$_2$e, computed as an average annuity over the 2010–2030 period with a 4% discount rate)

		RFS2 75%	RFS2 Baseline	RFS2 125%	RFS2 150%	RFS2 high corn
GHG emissions savings in the United States	Baseline	-16	-32	-49	-66	-22
	Yield growth 0.5%	-18	-33	-49	-67	-23
	Yield growth 0.2%	-19	-37	-57	-79	-25
Additional GHG emissions in the rest of the world	Baseline	17	34	61	88	51
	Yield growth 0.5%	27	45	79	120	63
	Yield growth 0.2%	24	54	107	175	87
Ratio savings over additional emissions	Baseline	-94%	-94%	-79%	-75%	-42%
	Yield growth 0.5%	-67%	-73%	-62%	-55%	-36%
	Yield growth 0.2%	-82%	-68%	-53%	-45%	-28%

Figure A1. Percentage change in global production per crop relative to baseline yield growth in 2030 in the RFS2 baseline scenario

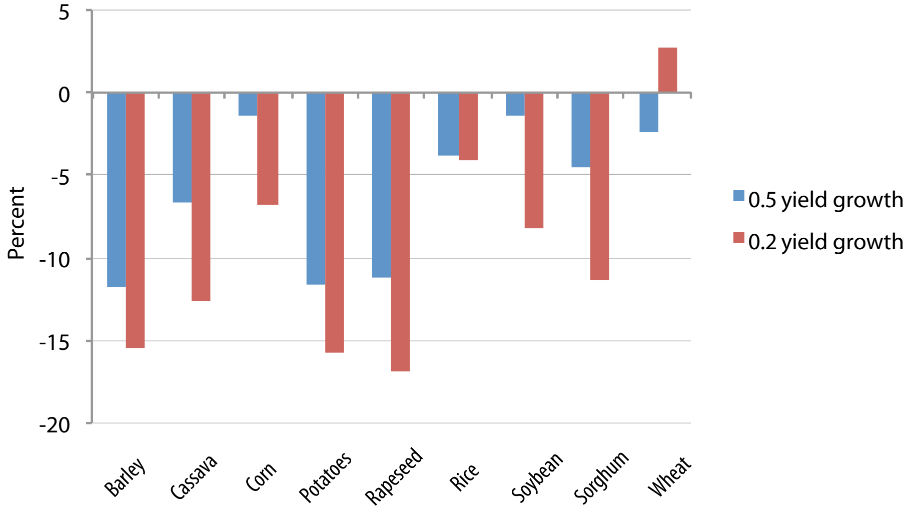


Figure A2. Share of imports in global demand in 2030 in the RFS2 baseline scenario

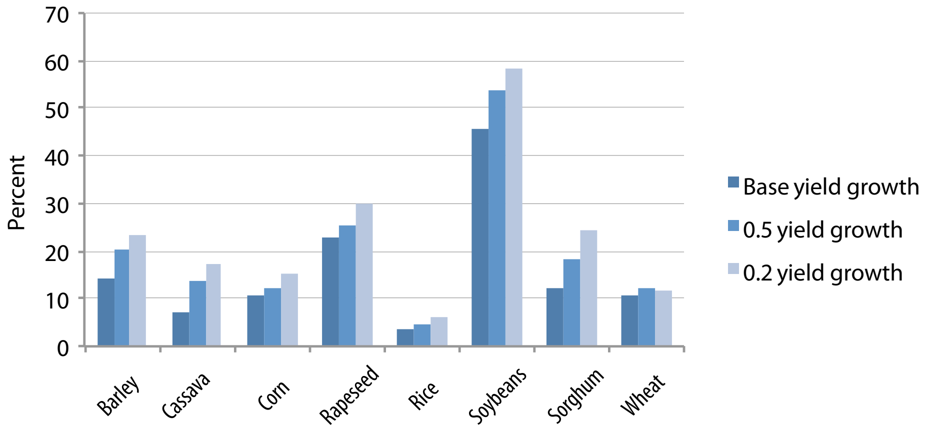
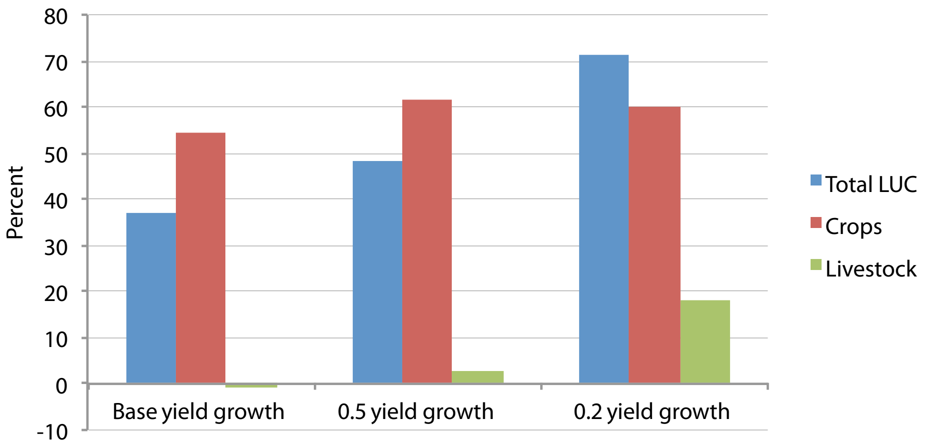


Figure A3. Absolute differences in global GHG emissions by source in the RFS2 150% scenario relative to the baseline biofuel target under varying assumptions about exogenous productivity growth (in Mt CO_2e) over the 2010–2030 period



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