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Article

Biofuels and the Future of Food: Competition and Complementarities

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Abstract: In this paper, we draw the key linkages between future biofuels growth on agricultural commodity prices, and highlight some of the key uncertainties over OECD fuel and energy policies, and their implications for global agricultural markets and the world food situation. Our results show some of the implications that biofuels expansion has on crop area expansion in regions where environmental concerns exist over land use change and the possible impacts on the environment. We also point to some promising areas for future research and specify some implications for policy interventions.

Keywords: biofuels; agriculture; agricultural markets and trade; food security

1. Introduction

As global energy resources become increasingly scarce in the face of growing energy demand for transport fuel and other productive uses, many countries have begun to turn to the possibilities that biofuels from renewable resources could offer in supplementing their domestic energy portfolio. The global biofuel markets are dominated by three key regions—the US, the European Union and Brazil. Each of these regions has its own particular approach to biofuels policy, which is important to capture when trying to understand the effects they have on markets. Brazil and the US represent almost 90% of bioethanol production, while more than 90% of biodiesel production is concentrated within the EU. However, other regions are expected to have a growing share of production in these biofuels categories, in the coming decades such as the United States, Argentina and Brazil [1].

There are various reasons for biofuels expansion, such as the need for energy independence, to support agricultural sector and rural incomes, or to reduce carbon emissions. Not all of these targets, though, may be compatible, and a policy that is purely aimed at producing renewable fuels—like the current RFS policy of the US—may not be as effective at reducing carbon intensity in fuels, as a low-carbon fuel standard would be, like the one current in force in the US state of California [2,3].

The linkages between energy and agricultural markets that have been discussed in the empirical literature, has mostly centered around the effect that biofuels expansion has on agricultural market prices for food and feed [4,5]. While a number of authors argued for a strong link between biofuels and food prices in the 2007–2008 food price spike [6–9], others have argued against a "food-*versus*-fuel" tradeoff, based on evidence collected in the period following the 2007–2008 price spike and leading into the global financial crisis [10]. The recent paper [11] argues that even though the increase in maize prices during the 2007–2008 period was linked to the growth in US biofuel production—the tax credits given to the blenders of ethanol were a minor determinant in that growth, compared to purely market-generated forces for investment. All of these analyses depend on some quantification of the role that biofuel play in agricultural markets—and require some kind of multi-market economic modeling framework to rationalize and understand these complex linkages.

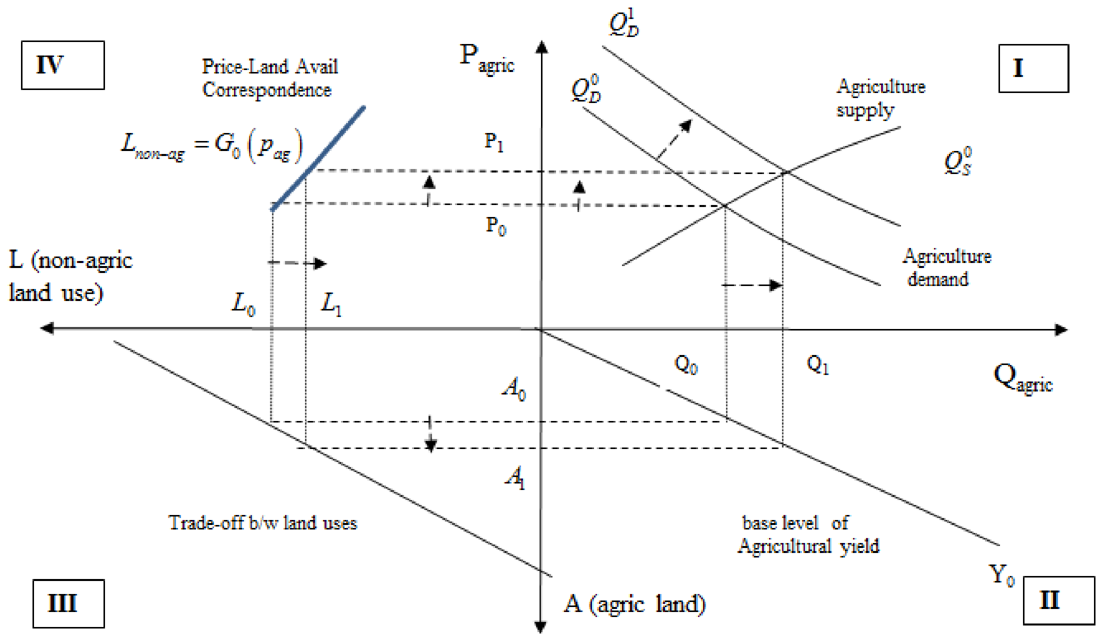
In this paper, we draw the key linkages between biofuels growth, agricultural market prices and agricultural land expansion that are of relevance to food security and the environment, and highlight some key uncertainties for policy. We first motivate the linkage between biofuels and agricultural market and environmental impacts, with a simple theoretical framework. Then we use a newly-modified version of the IFPRI IMPACT model, to illustrate the impacts of biofuel-related drivers of change on future agricultural market and environmental outcomes. Through comparing policy-relevant scenario outcomes to the model baseline, we are able to illustrate the impact that technology- and policy-oriented interventions might have on levels of future food security, and to prioritize the areas of scientific uncertainty that need to be addressed by future research.

2. Conceptual Linkage of Agricultural Markets to the Environment

Here we present a relatively simple conceptual model to discuss the linkages between biofuels and the environment more closely, with special attention to the role that productivity plays in mitigating (or exacerbating) the outcomes of the market equilibrium on the environment. The diagram below (Figure 1), shows how shifts in the supply-demand equilibrium relate to changes in agricultural land usage and the role that agricultural productivity plays in moderating those effects.

From this treatment, we see that a shift in the demand curve for the agricultural good (due to an increase in feedstock demand for biofuel production)—from Q_D^0 to Q_D^1—causes the price of the good to rise from P_0 to P_1, holding the supply curve fixed (which may be the case in the short-run). The increase demand for the agricultural good, and the increased level of production needed to meet it, causes the agricultural land usage to expand from A_0 to A_1, for a given level of yield (*i.e.*, productivity per unit area) at y_0. This increase in agricultural land usage decreases the area available for other land uses, and shifts that quantity from L_0 to L_1. Therefore, we can draw a correspondence between the price of the agricultural good and the availability of land for non-agricultural uses as the line $G_0(\bullet)$, which depicts a functional relationship such as $L_{\text{non-ag}} = G_0(p_{ag})$.

Figure 1. Linkages between biofuel-driven market shifts and agricultural land use in base case.

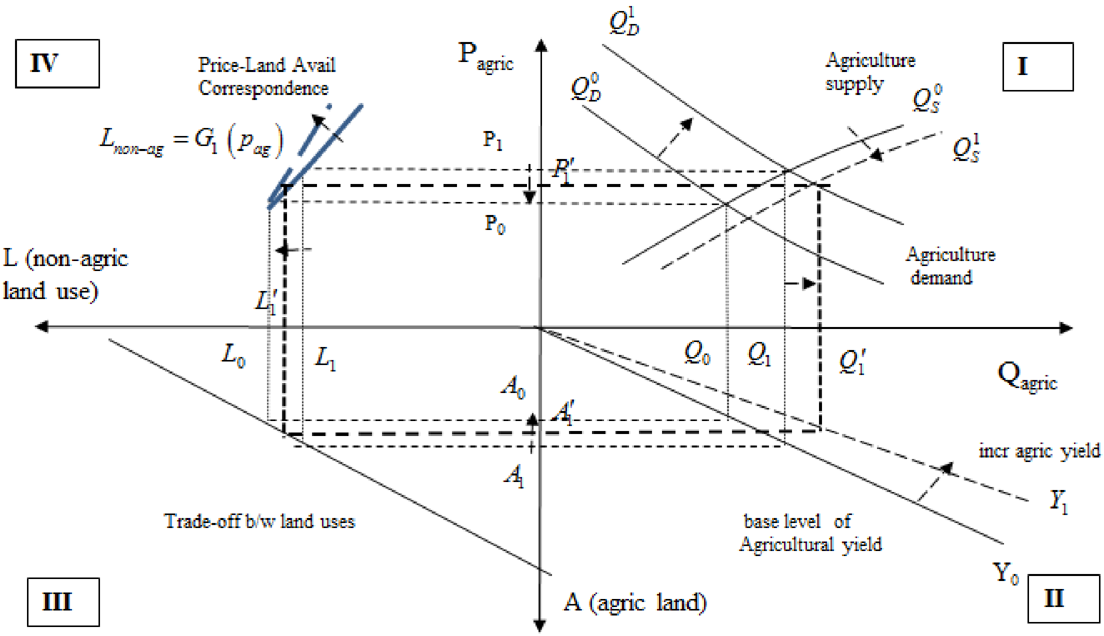


In the case where productivity is able to respond to the increased price (in the longer-term), then the line which describes yield can pivot to y_1 in order to give the same level of agricultural production on less agricultural land (Figure 2).

The supply curve, in such a case, would be expected to shift from Q_S^0 to Q_S^1 and the price levels would be reduced from P_1 to P_1'. This resulting shift in yield and production, would lead to a new level of agricultural land usage at A_1', which is lower than before (A_1), and which entails a higher level of land availability for non-agricultural uses (L_1'). By following the correspondence between prices and non-agricultural land availability in this updated case, we would obtain a new correspondence $G_1(\bullet)$, whose slope suggests that the decrease in the availability of land for non-agricultural uses is less for the same increase in prices, compared to the previous case with $G_0(\bullet)$.

If we were to think of the availability of land for non-agricultural land uses as being closely connected with land for natural cover (forest, shrubland, grassland, *etc.*), wildlife habitat and other non-agricultural human uses—then the increase in agricultural productivity has given a "land-saving" effect that allows expansion of production with less area expansion. In the discussion of the environmental impacts of future agricultural expansion, the issue of yield and productivity gains has been considered a key and decisive element in the avoidance or mitigation of adverse environmental impacts.

Figure 2. Linkages between biofuel-driven market shifts and agricultural land use with price-induced productivity increase.



Now, we will move the discussion of biofuels, agricultural markets and the environment from the conceptual framework that we have been discussing towards an empirical context, within which we use an equilibrium model of global agricultural and biofuel markets. This will allow us to relax a number of restrictive assumptions that were necessary to derive the analytical system of equations that we used for our simple conceptual exercise. By accounting for all of the major agricultural goods, along with their supply, demand and trade responses, as well as their linkage to the global biofuel markets, we can look at a much richer set of issues and account for a wider range of driving forces and entry points for technological and policy interventions.

3. Modeling Biofuels-Agriculture Linkages

In this section, we summarize the basic features of the IMPACT model and describe how it links the market for biofuels to the global agricultural market. This will provide a useful background to understanding how it will be applied in expanding our understanding of the key relationships between biofuels and agriculture, beyond our simple, conceptual construct.

3.1. The Basic IMPACT Model

The IMPACT model was initially developed at the International Food Policy Research Institute (IFPRI) to project global food supply, food demand, and food security to 2020 and beyond [12]. It is a partial equilibrium agricultural model that includes over 45 crop and livestock commodities, including cereals, roots and tubers, meats, milk, eggs, oilseeds, oilcake, vegetable oils, sugar, fruits, and vegetables. IMPACT has 115 country (or, in a few cases, country aggregate) regions, within each of which supply, demand, and prices for agricultural commodities are determined. Large countries are further divided into major river basins, which gives a total of 281 sub-national units that form the basis for livestock and irrigated/rainfed agricultural crop production. Crop production in impact is divided between area and yield response functions, and on the demand side by relationships for usage as food, feed, oilseed crush and the demand for biofuels production. (There is also the demand of "other" uses which is not price responsive and accounts for the residual utilization given in FAO data, which we do not directly model. These account for usage in industrial or other value-added sectors that are outside of the agricultural focus of the IMPACT model.) Demand and supply are both price responsive, and are balanced with levels of exports and imports to the world market that are made to balance at the global level.

A number of exogenous drivers are incorporated into the IMPACT model, both on the supply and demand side. On the supply side, the critical exogenous drivers of growth are those for yield growth and area expansion. Water availability (simulated by a separate but linked model) is also a determinant of future yield growth. On the demand side, the key drivers for change are those for population and income growth—which impact both the size and composition of future agricultural demand. For rapidly-growing and emerging economies in Asia, Latin America and Africa, these drivers are critical in shaping the future agricultural landscape through the influences they exert in closely-linked agricultural markets and patterns of trade.

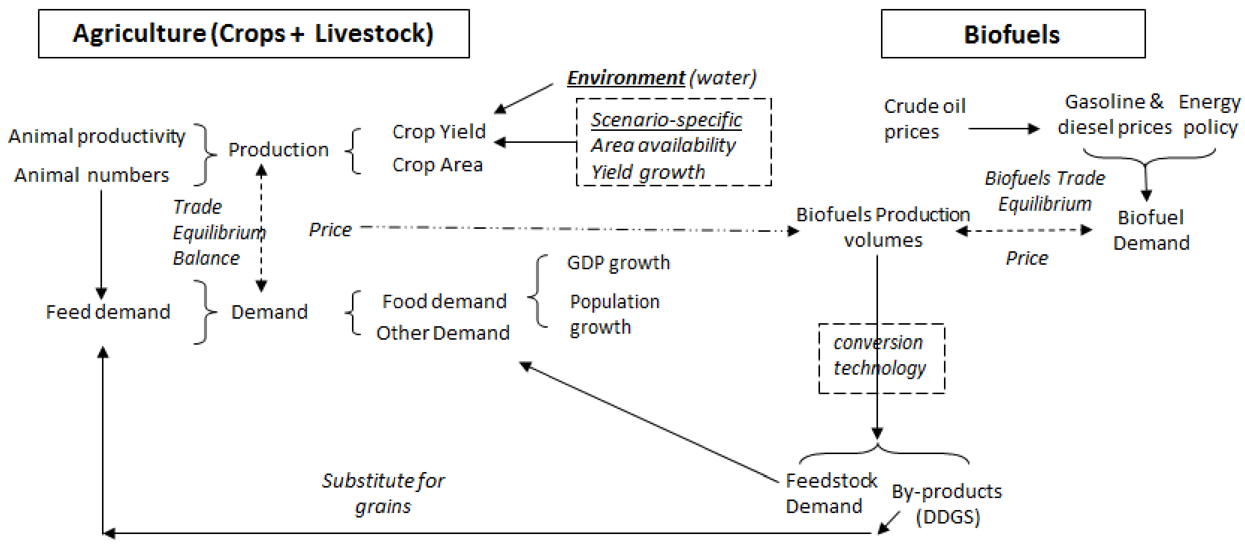
3.2. Modeling Biofuels Markets and Their Linkage to Agriculture

As an extension to earlier versions of the IMPACT model, a detailed module for ethanol and biodiesel markets were added to improve the linkages between the energy sector and the agricultural sector—which are becoming increasingly important in understanding the future of agricultural market dynamics. For ethanol, we consider major feedstocks such as feed grains, sugarcane and sugar beet, roots and tubers, and cover a variety of technologies, such as those which use sugarcane directly (as in Brazil) and those which use the by-products of sugar production (*i.e.*, molasses), as is the case in India and other countries. For biodiesel, we consider a wide range of oil-bearing crops that are used as feedstocks for production. We have also accounted for the by-products of biofuel production that can be used as animal feed (such as the dried distillers grains and solubles, DDGS).

Exogenous projections of transportation demand for fuel were taken from external sources which use complete models of the energy economy, which, in our case, was the Energy Information Administration of the US [13]. The policies for blending of biofuels with fossil-based fuels are used as a way of translating these exogenous projections of total fuel demand for transport into the policy-driven demand for biofuels, which is then balanced with biofuels supply and trade, at a global level. The resulting equilibrium model of ethanol and biodiesel production, consumption and trade, are linked with the global agricultural production and trade model in IMPACT. The key linkage between the two "sides" of the augmented model of agricultural and biofuel markets is in the feedstock demand for biofuels, which drives the supply side of the biofuels markets and the demand-side of the agricultural markets. This provides the same linkage as the feedstock demand variable (Q_d^{bioF}) in the conceptual model discussed earlier, and is also influenced by the price of the agricultural feedstock crop as well as of the biofuel product itself. In the model both area and yield respond to higher prices, which gives the adjustment along the extensive and intensive margins of production that was discussed within the conceptual framework.

The model linkages shown in Figure 3 illustrate how the various components of the energy and agricultural sector modeling are tied together.

Figure 3. Schematic of quantitative modeling components.



From Figure 3, we see the translation of biofuels supply into tonnage of feedstock crops demand, which is added, together with the demand for food, feed, crush and other uses, to the total demand within the agricultural trade model. This increase in demand causes the supply side of the agricultural model to adjust, in terms of crop prices, area, and yield, while there might also be adaptation within international biofuels markets, through trade in the biofuel products themselves.

Since most available biofuels data start in 2005 calendar year, we use 2005 as the base year of the biofuels model (although the simulations of the larger IMPACT model begin from year 2000). Biofuels model parameters have been calibrated to 2005 historical data. Further description of the key equations of the biofuels model is given in the Technical Annex.

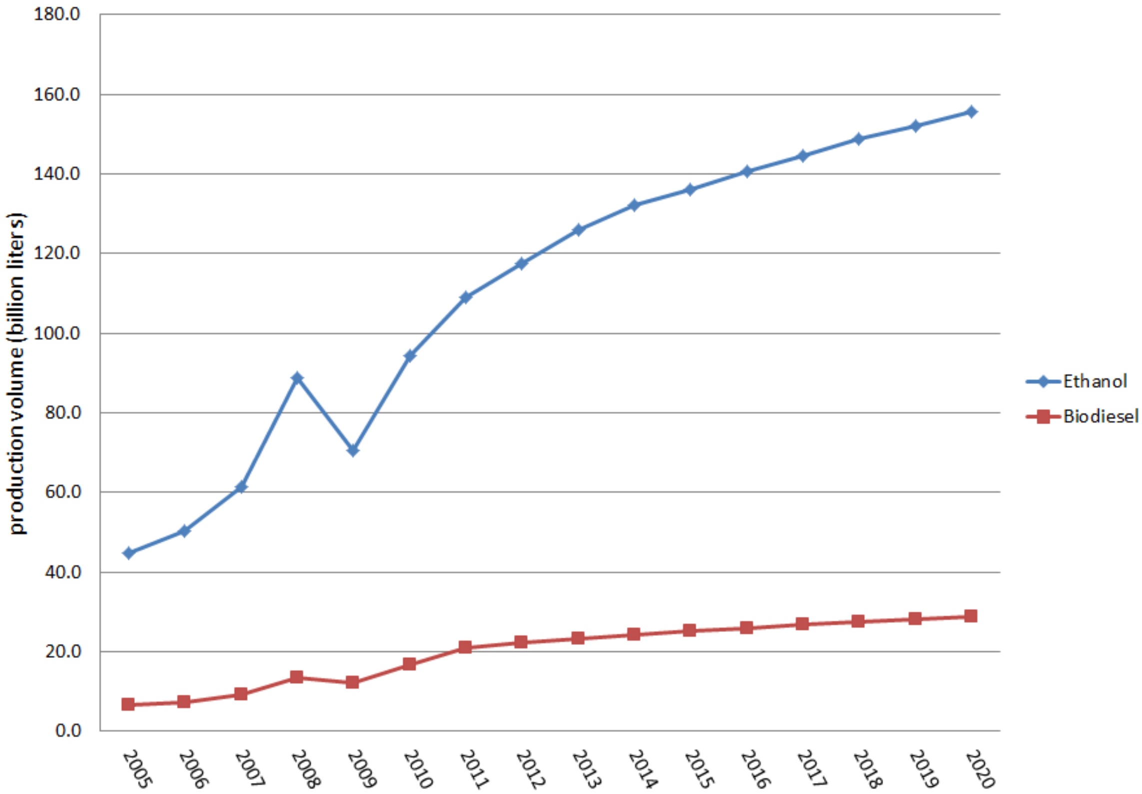
4. Baseline and Key Scenarios for Biofuels

Using the model described in the previous section, we now show the implications of biofuels production and consumption growth on the medium- to long-term dynamics of agricultural markets. We will contrast the model baseline with a few illustrative scenarios that highlight the impact of key policy- and technology-related interventions on both the agricultural and biofuel markets, as well as on the agricultural landscape.

4.1. Baseline Projections with Biofuels

In Figure 4 we see that the global volumes for both ethanol and biodiesel production have risen steadily over time, from their levels in 2005—with the sharp increase to 2008 corresponding to the period during which prices for cereals and other agricultural products were increasing rapidly.

Figure 4. Global ethanol and biodiesel production under baseline case.



This is followed by a drop as global oil prices dropped and biofuels production capacity adjusted to a new period of tight feedstock markets and closely-linked levels of profitability in the renewables sector. The future projections of ethanol and biodiesel show a more modest rate of increase into the future, compared to the rapid increase in the years immediately following 2005—and reflect the need to meet the blending mandates within the US for conventional (corn-based) ethanol through 2015. How the additional mandates for more "advanced" ethanol will be met after that period (through 2022 and beyond) under the current Renewable Fuels Standard of the US remains a key source of policy uncertainty, as it is unlikely that cellulosic-based technologies will be able to scale up to the production levels that are currently mandated for the years following 2015.

Figure 5 shows the share of global biofuels production that is traded and illustrates the increasing importance of global markets in enabling growing demands for renewables to be met in the major OECD economies that consume and produce biofuels—such as the US and EU—and important non-OECD countries such as Brazil.

Whereas there were relatively few "players" on global biofuels markets in 2005, that number has grown and will result in new producers coming online and trading their products with regions that have more developed consumption mandates and policies. The demand on the various feedstock crops that is implied in these levels of biofuel production is captured in Figures 6 and 7, which show the share of feedstock usage across various commodities for ethanol and biodiesel production, respectively.

Figure 5. Traded shares of global ethanol and biodiesel production.

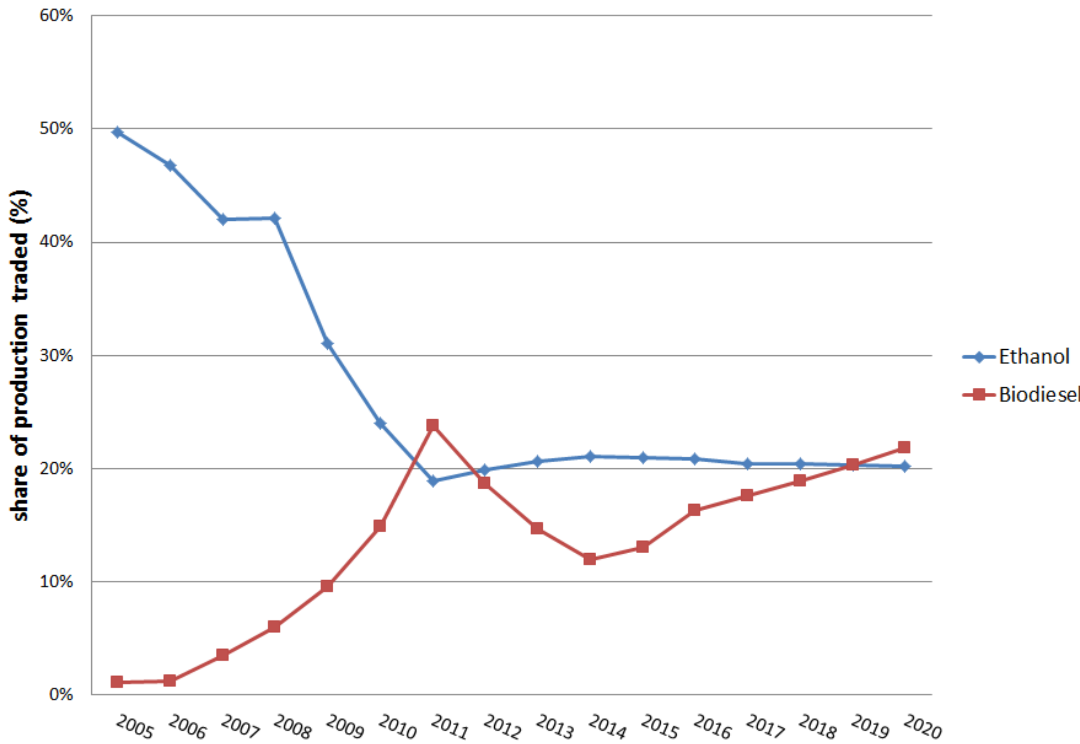


Figure 6. Share of total feedstock tonnage used in global ethanol production from various sources.

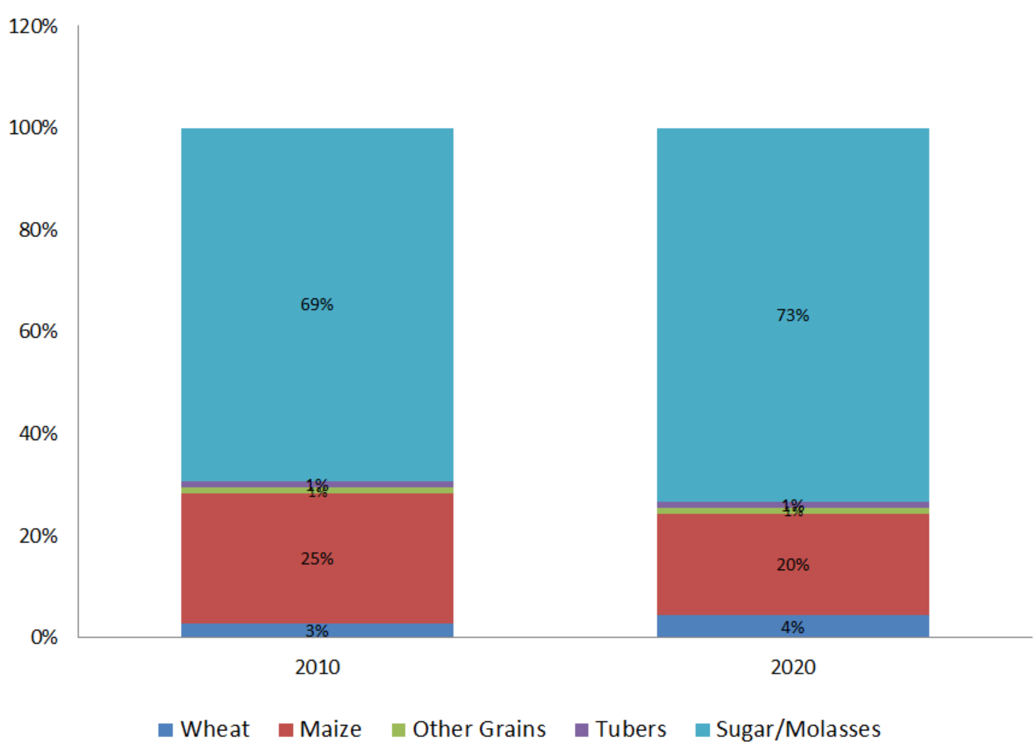
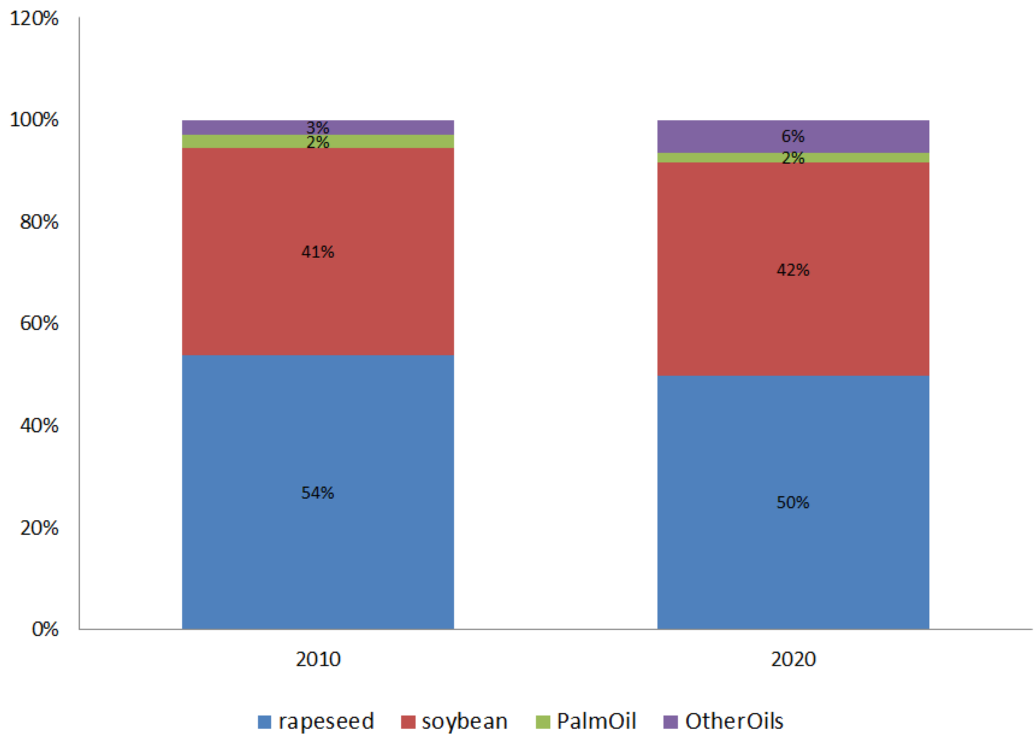
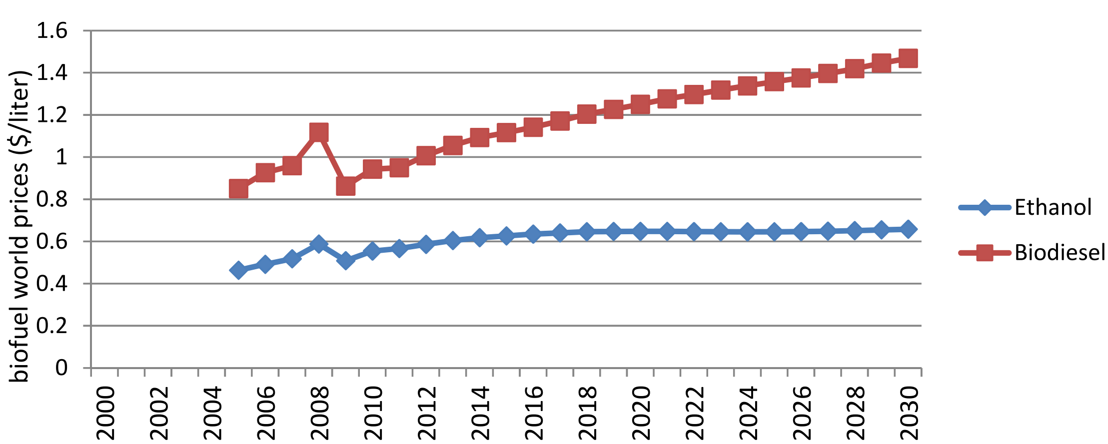


Figure 7. Share of total feedstock tonnage used in global biodiesel production from various sources.



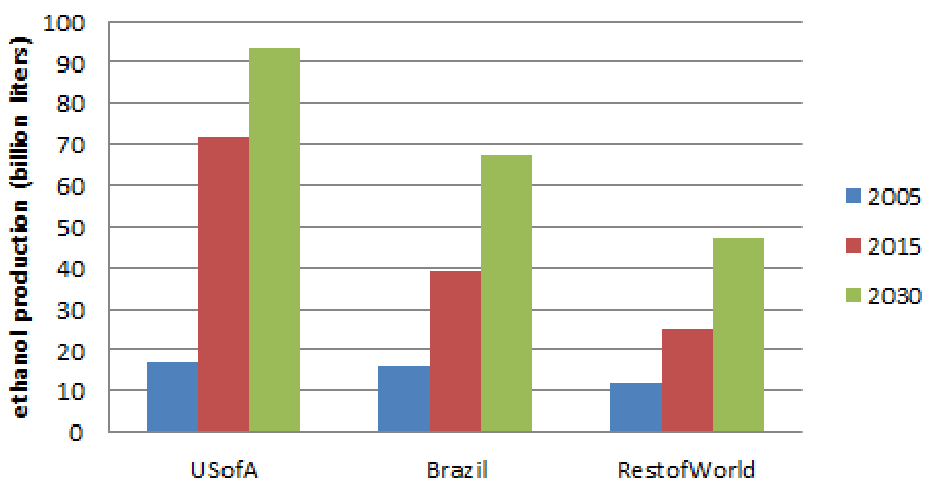
This distribution of feedstocks already indicates what we'd expect the relative pressure of future biofuels growth on various agricultural markets to be, and implies that those markets with a heavier share of feedstock usage (*i.e.*, sugar for ethanol, and rapeseed oil for biodiesel) will need to adjust more as future growth of ethanol and biodiesel develop. The relatively slow growth of future biodiesel production, compared to that of ethanol, indicates that the upward price pressures on oils—which competes directly with growing food uses—will be a major constraint to their future growth, compared to the supply of sugar- and starch-based feedstocks for ethanol. In Figure 8, we see the evolution of biofuel prices over the baseline case.

Figure 8. World prices of ethanol and biodiesel under baseline.



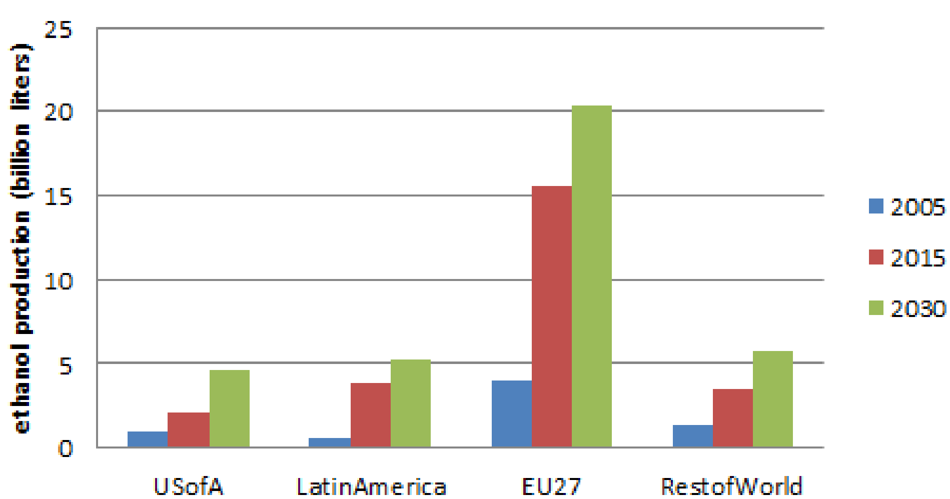
Which shows a more vigorous growth of ethanol production, in line with the increasing demands that are expected in the US and Brazilian markets. The distribution of ethanol production among the major regions is shown in Figure 9, which shows the expected rapid growth of the US (labeled "USofA") to 2015, after which the conventional (maize-based) ethanol mandate will remain constant—although further (slower) growth is expected. Brazil and the Rest-of-the-World ("RestofWorld") are also depicted in this figure.

Figure 9. Ethanol production in major regions under baseline.



The overtaking of Brazil by the US in ethanol production volume is also notable in these results, although the rate of growth in Brazil (and the rest of the world) is expected to be more rapid after 2015, compared to the US—whose "blending wall" provides a limit to ethanol use in the transportation pool, which can only be increased by further penetration of flex-fuel vehicles. In terms of biodiesel production, the projections of production volumes are shown in Figure 10, in which we see the dominance of the EU27 region of the world biodiesel market.

Figure 10. Biodiesel production in major regions under baseline.



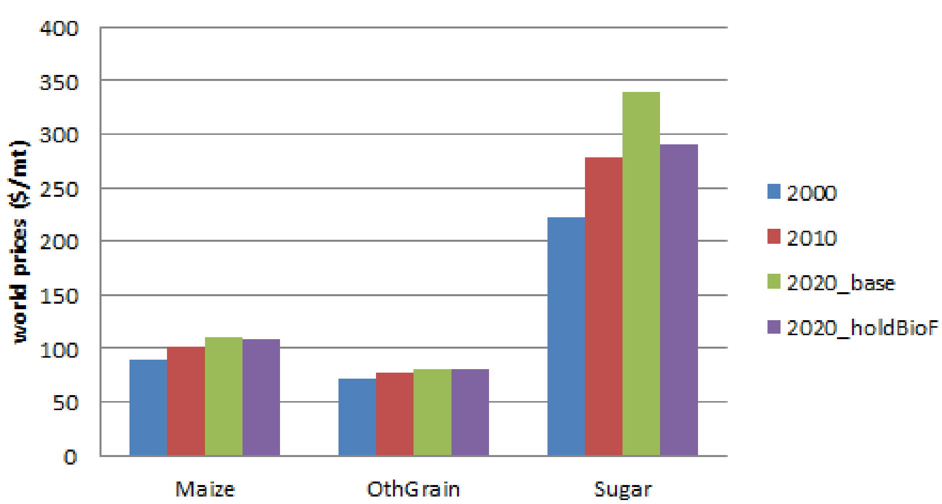
The rate of increase in biodiesel production in Latin America to 2015 is fairly large, as is that within the EU region—although, the rate of increase sharply falls off in the period between 2015 and 2030. The rate of growth in the US is greater in the period after 2015, and is expected to nearly reach the level in Latin America. Throughout the projection period, the share of the EU region in global biodiesel production falls from nearly 60% to slightly over 50% by 2030, indicating the magnitude of its targets for blending.

4.2. Impact of Biofuels: Scenario Analysis

In this section, we now consider some alternative scenarios which help to illuminate the impact of biofuels on agricultural markets, and what the implications are for prices and welfare. To illustrate the effect of biofuels on markets, in the clearest possible way, we consider an alternative scenario in which the level of biofuel production is held constant at a certain point in the projection horizon (2010, in our case), so as to contrast the evolution of feedstock demand and prices relative to the baseline in which biofuel production (and feedstock usage) proceeds at the levels described in the previous sub-section. Even though "freezing" biofuels at a particular level is not practically possible—this type of counterfactual best isolates the effect of biofuels on the rest of the world agricultural market, and helps to better trace the causality in market price changes, holding other drivers constant.

In Figure 11, we see the difference in the world market prices of major ethanol feedstocks—such as maize and sugar—between the baseline case and the case in which ethanol production is held constant at 2010 levels.

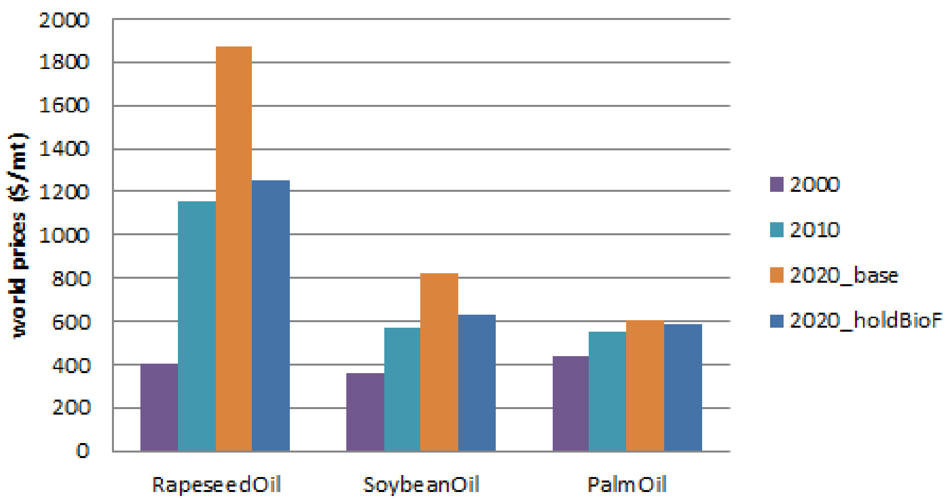
Figure 11. Ethanol feedstock prices under baseline and scenario.



We see that the effect is largest on world sugar markets, compared to the markets for maize and other coarse grains. This indicates that the biggest impact on maize markets, from (mostly US) ethanol production would have already been felt by 2010, with the further increases adding relatively little to the future growth. This matches with what we observed in Figure 9, where we saw the fastest growth in US ethanol production occurs in the first 10–15 years of the projection horizon. Brazil, by contrast, has a large increase in ethanol production in the period from 2015 under the baseline (Figure 9), so the effect of holding sugar-based ethanol constant at 2010 levels, in the alternative scenario, creates a much larger contrast in terms of production volume and sugar prices (Figure 11).

If we look at the case of biodiesel feedstock prices (Figure 12), we see that the impact of holding biodiesel production levels constant at 2010 levels has a very large impact on rapeseed oil prices, as well as that of soybean oil prices.

Figure 12. Biodiesel feedstock prices under baseline and scenario.



The effect of this scenario on palm oil prices is relatively small, given that it has a relatively small share in the overall volume of biodiesel feedstocks (Figure 7), compared to rapeseed oil and soybean oil. Given the food demand for vegetable-based oils is expected to increase to 2030 and beyond, globally—this direct competition between food and feedstock uses implies that price pressures will be significant and growing over time.

5. Food Security Implications of Biofuels

In order to illustrate what these impacts mean for food security in developing countries—we translate the levels of per capita utilization for food, across all commodities, for each region, and show how they change from the baseline case. In Table 1, we see that the levels of calorie availability food increase in all regions, on a per capita basis, as a result of holding biofuels production fixed in the alternative case. Note that we refer to these quantities as "availability" of calories, as the actual intake might be less than this, due to losses in food preparation or wastage at the household level. These are calculated directly from the model-generated food consumption quantities, and represent the most that can be derived at the observed levels of utilization as dietary energy.

The largest increase in percentage terms is in Latin America region, a major producer of biofuels. Growth in biofuels represents an average of 37 kilocalories per capita per day in food availability across the developing countries as a region. While this represents a 1.4% difference and may not seem like a very significant difference—when we translate that into implications for malnutrition in the most vulnerable demographics of the developing world (young children), it takes on a different dimension.

Table 2 shows the implications of the alternative scenario on malnutrition among children aged zero to five, in various regions of the world.

Table 1. Per capita calorie availability from food under baseline and scenario (kilo calories per person per day).

Region	2000	2010	2020		
			Baseline	Biofuels held at 2010 levels	Difference
South Asia	2333	2348	2412	2449	37
All Asia	2638	2705	2801	2835	34
All SS Africa	2174	2150	2245	2268	23
Latin America	2850	2769	2796	2859	63
WANA	3129	3075	3112	3163	51
All Developing	2639	2661	2734	2771	37

Source: author simulations with IMPACT model.

Across all regions, there is a decrease in the number of malnourished children—with the largest decreases occurring in Asia (and mostly centered in South Asia, where roughly half of the developing world's malnourished reside). So, the overall decrease in child malnourishment in the developing world of 1.4% translates to alleviation of malnourishment for nearly 2 million children, which is not a trivial number.

Table 2. Child malnutrition levels under baseline and scenario (undernourished children aged 0–5, millions).

Region	2000	2010	2020		
			Baseline	Biofuels held at 2010 levels	Difference
South Asia	77.5	74.6	69.5	68.9	−0.7
All Asia	101.9	94.8	85.5	84.5	−1.0
All SS Africa	32.0	39.9	43.0	42.6	−0.4
Latin America	7.7	7.9	7.3	7.0	−0.3
WANA	6.0	6.6	5.9	5.7	−0.2
All Developing	148.1	149.7	142.1	140.2	−1.9

Source: author simulations with IMPACT model.

We derive these impacts from an estimated empirical relationship [14], in which the percentage of malnourished children under the age of five is estimated from is estimated from the average per capita calorie consumption, female access to secondary education, the ratio of life expectancy of females over males (at birth) and access to water and sanitation. The per capita calorie consumption variable is derived from two components, which include the amount of calories obtained from commodities included in the model, as well as calories from commodities whose consumption levels are not modeled explicitly (but are contained within the FAO country-level food balances). In these scenarios we keep all factors constant, within this relationship, except for the calorie availability which is generated endogenously from the per capita food consumption simulated by the model.

6. Land Use Implications of Biofuels

In terms of land use change, we see that there is an implication for crop area under the scenario in which biofuels growth is held constant. In Table 3, we see the difference in crop area expansion over time, when we compare the baseline case to the alternative scenario.

Table 3. Total crop area under baseline and scenario (millions of hectares).

Region	2010	2020		
		Baseline	Biofuels held at 2010 levels	Difference
North America	74.1	80.2	79.8	−0.4
Europe	75.0	78.2	77.5	−0.7
Latin America	27.9	30.8	30.4	−0.4
China	252.3	268.1	266.7	−1.4
S Asia	269.7	295.5	293.7	−1.8
SE Asia	44.7	46.6	46.4	−0.1
Other E Asia & Pacific	17.7	17.9	17.8	−0.1
SS Africa	18.2	21.8	21.7	−0.1

Source: author simulations with IMPACT model.

The greatest "savings" in crop area expansion are seen in China and South Asia—the areas of Asia which are already under the greatest pressure from population growth and other demands on available area. The composition of crop area changes that comprise the total area changes differ across different regions, but are fairly consistent. In Table 4, we see that wheat and maize are the cereals that have the greatest changes in area under the scenario. Given the importance of wheat as a food grain, it sees the greatest savings—especially in South Asia.

Maize is mostly a feed grain in most regions, except for Sub-Saharan Africa and parts of Latin America. Soybean, which is also an important crop for feed uses, undergoes the largest change in China, where it is in high demand for the livestock sector, and which receives large imports from North and South America. When growth of soybean-based biodiesel is halted, under the scenario, the increases that would otherwise be needed in China to make up for reduced import availability are avoided. The impact on rapeseed area is greatest in South Asia, where food oils are in high demand and are mostly imported from other regions of the world—which suggests that the alternative scenario makes more imports available to South Asia and avoids the area increases that would otherwise be necessary to meet domestic demand. The large savings of sugarcane area in Latin America point to the impact of the scenario on sugar-based ethanol production in Brazil, and the avoided area increases of sugarcane in South Asia also represent large water savings, given that much of the sugarcane in regions like India are irrigated from scarce water resources (as is the case for wheat in South Asia and China).

Table 4. Changes in crop area from baseline in 2020 (thousands of hectares).

Crop	North America	Europe	Latin America	China	South Asia	SE Asia	Other E Asia & Pacific	SS Africa
rice	−6.2	−3.1	−5.9	−149.6	−27.3	0.8	−17.5	−11.4
wheat	−87.5	−507.3	−12.0	−776.3	−1155.6	−10.9	−53.2	−28.6
maize	−40.5	−53.7	−13.2	−159.8	−57.2		−3.9	−9.0
other coarse grains	−15.8	12.9	−7.2	−2.8	−15.5		0.1	−16.3
soybean	−170.0	−2.0	−0.6	−221.9	−100.3	−2.9	−6.6	−1.0
roots & tubers	0.3		−0.9	−0.1	−2.6	0.0	0.1	−0.2
sugarcane & beet	−60.6	−104.0	−307.2	−38.0	−240.0	−124.7	−23.5	−72.2
vegetables & fruits	8.5	5.1	3.5	15.3	2.4	2.6	1.3	2.4
pulses					−3.6		−0.1	
rapeseed	−54.7	−58.1	−1.2	−88.5	−166.0			
Other oil crops	17.4	−19.0	−29.1	−3.9	−37.7	−1.1		−11.8
other crops	29.9	14.9	−2.8	−21.2	−2.2	−2.2		−0.3

Source: author simulations with IMPACT model.

7. Implications of Food-Energy Interactions for Policy

Given these results, we can infer the implied pressure on land resources that is embodied in biofuels production. In regions where irrigation is needed for many of these crops, this pressure on land also translates to water resource consumptive use. In this analysis we have not looked at the carbon emissions from these land uses, which would capture another aspect of the environmental impact of biofuels that many researchers have looked at—beginning from the work of [15], which highlighted the "indirect" land use change (iLUC) impacts of biofuels, and which was followed by a number of other articles that sought to confirm and even challenge their implications.

In this paper, we do not attempt to come up with a particular quantitative measure of the iLUC impact that is associated with a particular fuel path, given the inability to resolve a number of issues regarding model-based uncertainties and methodological issues that lead to differences across the iLUC effects calculated by different models. The iLUC effect is, itself, an endogenous outcome of the quantitative analysis and the particular model used to generate it, and its estimates—including those used to derive an "iLUC factor" which is applied in ranking the environmental sustainability of various biofuels feedstocks.

Some research efforts have been underway to try and understand the differences between models and types of iLUC effects that they generate, and we summarize a set of results, as an illustration of this, in Table 5, below.

Table 5. Land use change effects in different models.

(land use change in hectares per toe of biofuels)	US ethanol		EU ethanol	
	maize	wheat	coarse grains	wheat
IMPACT model	0.12	0.22	0.29	0.22
AgLink model	0.51			0.57
FAPRI model				0.39
GTAP model	0.16			0.79
LEITAP model	0.86			

Source: [16].

These results are drawn from a recent comparison study by [14], which tried to subject various models to biofuels shocks in order to illustrate (and understand) the differences in impacts on land use change among them. Among the many factors that underlie these differences are those of basic model structure, since some of the models are partial-equilibrium in nature (like the IMPACT, AgLink, FAPRI models) and focus mainly on agricultural markets and consumption, whereas other models take all interactions within the economy into account (like GTAP and LEITAP) and bring all markets (including input markets for labor, capital and chemical inputs) into equilibrium, with respect to the behavior of the agents within the economy. Some differences come from the way in which the by-products of biofuels are handled—which offsets the decrease in feed demand when grain or oilseeds are used for biofuel feedstock production. Other differences come from the variation of parameter values used for key behavior relationships, such as the response of area or crop yield to price, which differ according to the particular form of the functional relationship that's embedded in the model (linear *versus* non-linear, *etc.*). The differences in how models handle trade also affects these results—as some models have a detailed bilateral representation of trade flows, such as in the GTAP models, *versus* a "pooling" of total net trade from all countries within an integrated world market, as is the case with many partial-equilibrium models. Indeed, there is a constellation of possible influences that could lead to these differences, which have been discussed in more detail by other authors [17,18] than we are able to do in this short paper. It is worth bearing these differences of measurement in mind when deciding how best to carry out *ex ante* environmental assessments of biofuels, and how to use them within the process of policy design or implementation.

8. Conclusions

In this paper, we have explored the possible dimensions in which biofuel production could intersect with agricultural production, market prices, the environment and food security-related welfare measures. Our analysis shows that there are notable impacts of biofuels growth on agricultural commodity prices, and that those impacts can translate into changes in consumption, calorie availability and even food security (which we measured in terms of malnutrition risk for children). From both a conceptual point-of-view, as well as the results of the multi-market model that we have used—we show the linkage between biofuels expansion and land area that is used by agriculture. This implies that there are pressures on land resources that might have impacts on either loss of natural cover, competition with grassland or other uses for land like habitat and loss of soil carbon (although we have not quantified it here).

As further work, we will refine the analysis of land use change to better understand which exact types of land cover might be converted by crop area expansion, and to what extent adjustments in area under other uses might be needed—like pasture. This is an especially important issue for regions like Brazil, where much of the disagreement over iLUC-related analysis of greenhouse gas emissions hinges on the expansion behavior of sugar, soybean area and pasture-fed animals and how likely they are to infringe upon the Amazon region. This is likely to remain an active area of research, given that the sustainability of biofuels in both the EU and US are currently (and will likely continue to be) under policy review as to the true carbon-savings that they achieve, relative to fossil fuels.

From the perspective of food and agriculture—the future demands of energy for transport will continue to place pressure on land and other resources if starch sugar or oil-based biofuels remain a large part of the renewable energy mix. This will most certainly continue, given the relatively slow growth of cellulosic-based biofuels and their difficulty in achieving cost-competitiveness, relative to the current “first-generation” biofuels. Given this linkage between agriculture and energy, the evaluation of future food outlooks will have to constantly evaluate the share of total crop consumption and land use that biofuels embody, and consider a range of scenarios that go beyond the traditional focus on crop-specific policies that agricultural economists have had in the past. This will require a greater dialogue between the energy and agricultural modeling communities, and a common understanding of the technological possibilities and key policy issues that are of relevance to the interaction of food and energy markets.

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Technical Annex

In this annex, we present some additional details on some key aspects of modeling biofuels in IMPACT. Based on the domestic biofuel production that is possible within each region, any demand deficit that cannot be met by own-production must be satisfied through international trade in biofuel products. Given that the IMPACT model only treats international trade in agricultural commodities, at present, we have constructed a separate equilibrium model to represent the adaptation that is plausible within international biofuel markets.

For the period of 2000 to 2004, we model biofuels feedstock demand using exogenous growth rates estimated based on historical data for 2000 and 2005. In this paper, we refer mostly to the endogenous modeling of biofuels throughout the discussion of the methodologies used for the development of the biofuels model. From 2005 onward, the modeling of biofuels follows approaches described below.

Biofuels demand equations:

$$Demand_{ethanol} = \max\left\{d_{eth} \cdot \left(P_{eth}\right)^{\varepsilon_{eth}} \cdot \left(P_{gas}\right)^{\varepsilon_{gas}}, Mandate_{ethanol}\right\}$$

where d_{eth} is the ethanol demand intercept, (P_{eth}, P_{gas}) are ethanol and gasoline prices (respectively), (ε_{eth}, ε_{gas}) are the respective ethanol demand elasticities with respect to the ethanol price and the gasoline price, and $Mandate_{ethanol}$ is the volumetric blending mandate for ethanol.

$$Demand_{biodiesel} = \max\left\{d_{bdsl} \cdot \left(P_{bdsl}\right)^{\varepsilon_{bdsl}} \cdot \left(P_{dsl}\right)^{\varepsilon_{dsl}}, Mandate_{biodiesel}\right\}$$

where d_{bdsl} is the biodiesel demand intercept, (P_{bdsl}, P_{dsl}) are biodiesel and diesel prices (respectively), (ε_{bdsl}, ε_{dsl}) are the respective biodiesel demand elasticities with respect to the biodiesel price and the diesel price, and $Mandate_{ethanol}$ is the volumetric blending mandate for biodiesel.

Ethanol supply equations:

- Feedstock-based ethanol production, which applies to feed grains, sugar cane and sugar beet:

$$QS_{ethanol}^{feedstock} = q_{eth}^{fdstk} \cdot \left(P_{eth}\right)^{\gamma_{eth}^{fdstk}} \cdot \left(C_{eth}^{fdstk}\right)^{\theta_{eth}}$$

where $QS_{ethanol}^{feedstock}$ is the production of ethanol, q_{eth}^{fdstk} is the ethanol production intercept, γ_{eth}^{fdstk} is the production elasticity with respect to the ethanol price (P_{eth}), C_{eth}^{fdstk} is the feedstock cost for ethanol, and θ_{eth} is the ethanol production cost elasticity.

The feedstock costs are the region-specific costs of ethanol production that affect the region-specific levels of ethanol production. To derive these costs, we start from the cost of ethanol production from feedstock crop j, which is a function of crop producer prices converted into US$ per liter using technical conversion rates for each feedstock. The cost of ethanol production from feedstock crop j is then summed over all feedstock crops used in a given region and weighted by the share of ethanol produced from each feedstock crop.

- Molasses-based ethanol production is a by-product of sugar production. Ethanol production quantity is calculated by converting the sugar production quantity to ethanol production using technical conversion factors estimated from historical data for 2005.
- Non-feedstock-based technologies include ethanol produced as a by-product of crude oil production and ethanol produced from cheese whey.

$$QS_{ethanol}^{non-feedstock} = q_{eth}^{nonfdstk} \cdot \left(P_{eth}\right)^{\gamma_{eth}^{nonfdstk}}$$

  where $QS_{ethanol}^{nonfeedstock}$ is the production of ethanol from non-feedstock-based technologies, and $q_{eth}^{nonfdstk}$ is the corresponding production intercept, $\gamma_{eth}^{nonfdstk}$ is the production elasticity with respect to the ethanol price (P_{eth}),
- Total ethanol production in each region is the sum of feedstock-based ethanol production, molasses-based ethanol production, and non-feedstock-based ethanol production.

Biodiesel supply equation:

$$QS_{biodiesel} = q_{bdsl} \cdot \left(P_{bdsl}\right)^{\gamma_{bdsl}} \cdot \left(C_{bdsl}\right)^{\theta_{bdsl}}$$

where $QS_{biodiesel}$ is the production of biodiesel, q_{bdsl} is the biodiesel production intercept, γ_{bdsl} is the production elasticity with respect to the biodiesel price (P_{bdsl}), C_{bdsl} is the feedstock cost for biodiesel, and θ_{bdsl} is the biodiesel production cost elasticity.

The region-specific feedstock costs of biodiesel production are formulated in the same way as the region-specific feedstock costs of ethanol production, where the costs of feedstock crops used in biodiesel are multiplied with the appropriate conversion coefficients and their share in total production.

Feedstock demand equations:

Biofuel feedstock demand is calculated by dividing biofuel production (weighted by the share of biofuel produced from each feedstock crop) by yield of biofuel per metric ton of feedstock quantity.

Endogenous share of sugar cane or beet crop going into sugar production:

In each time period, the variable of share of sugar cane (or beet) crop going into sugar production has to satisfy the following relationship:

Sugar cane (or beet) production × share of sugar cane (or beet) crop going into sugar production = Sugar cane (or beet) production − Feedstock demand for sugar cane (or beet)

Total commodity demand:

Total commodity demand = Food demand + Feed demand + Crush demand + Other use demand + Ethanol feedstock demand + Biodiesel feedstock demand

Biofuel net trade equation:

Ethanol net trade = Ethanol production − Ethanol demand
Biodiesel net trade = Biodiesel production − Biodiesel demand

We introduce a simple DDG model to capture the feed displacement effect of the by-product of ethanol production. We focus on the DDG production from the US, the largest DDG producer and exporter in the world. We establish the relationship between ethanol production (endogenously determined in the model) and DDG production using the technical conversation rate between the tonnage of feedstock demand for maize used by the ethanol sector and the quantity of DDG production. In the IMPACT model, the feed consumption of maize within the US is driven by the production of beef (and other livestock which consume maize) and the consumption of maize per unit production that is determined by animal-specific feed ratios. In essence, these feed ratios represent the conversion between the quantity of maize feed use and production of beef or other livestock fed with maize. We then estimate the share of total US maize feed consumption for cattle that is displaced by DDG, using historical data from USDA ERS. Finally, we derive the US domestic DDG feed consumption by multiplying this share with the total US maize feed consumption, which then allows the displaced tonnage of maize feed to be consumed by other livestock or added to exports of maize from the US. Finally, whatever DDG production that is not consumed within the US as feed for cattle, is exported to the rest of the world.

We also implement biofuel policies with regard to volume and percentage mandates on ethanol and biodiesel demand by setting lower bound for biofuel demand. The data for biofuels policies, specifically mandates are from USDA FAS GAIN Reports [19].

Key data sources and assumptions

Countries modeled in IMPACT for ethanol are Alpine Europe, Argentina, Australia, Baltic, Brazil, British Isles, Canada, Caribbean Central America Central Europe, China, Colombia, Cyprus, Ecuador, Egypt, France, Germany, Gulf States, Iberia, India, Indonesia, Iran, Italy, Japan, Kenya, Malaysia, Mexico, Malawi, Netherlands, New Zealand, Nigeria, Pakistan, Philippines, Poland, Russia, Scandinavia, South Africa, South Korea, Swaziland, Ukraine, United States, and Zimbabwe. Countries modeled in IMPACT for biodiesel are Adriatic, Alpine Europe, Argentina, Baltic, Brazil, British Isles, Canada, Caribbean Central America, Central Europe, China, Cyprus, Ecuador, France, Germany, Iberia, India, Indonesia, Italy, Malaysia, Pakistan, Poland, Scandinavia, South Korea, and United States.

In our current modeling efforts, we have come across a number of limitations relating to data—mostly relating to the parameterization of the behavioral characteristics of the model. Given the relatively "thin" economic literature on biofuels production, utilization and trade, there have been very few studies that can provide guidance as to what the long-term response of biofuels supply and demand is to market conditions. While European Union, Brazil and United States have been fairly well-studied, compared to most regions of the world, there is not nearly as much empirical evidence for other regions. Most studies are heavily biased toward OECD countries, and tend to leave out much of the developing world, when discussing behavioral response and growth potential.

Since most available biofuels data start in 2005 calendar year, we use 2005 as the base year of the biofuels model. Biofuels model parameters have been calibrated to 2005 historical data. For the Baseline projections, further calibration is conducted. To this end, available historical data after 2005 is used to compare model projections with actual data. Secondly, IMPACT biofuel projections are compared to biofuel market projections from other partial equilibrium and general equilibrium models. After these steps, Baseline projections are further calibrated using model parameters to generate projections that are in line with short-term and long-term market dynamics.