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The impact of biofuel growth on agriculture: Why is the range of estimates so wide?

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ABSTRACT

The rapid expansion of biofuel production has generated considerable interest within the body of empirical economic literature that has sought to understand the impact of biofuel growth on the global food economy. While the consensus within the literature is that biofuel emergence is likely to have some effect on future world agricultural market, there is a considerable range in the estimated size of the impact. Despite the importance of this topic to policy makers, there has been no study that has tried to reconcile the differences among various outlook studies. This paper undertakes an in-depth review of some key outlook studies which quantify the impacts of biofuels on agricultural commodities, and which are based on either general-equilibrium (GE) or partial-equilibrium (PE) modeling approaches. We attempt to reconcile the systematic differences in the estimated impacts of biofuel production growth on the prospective prices and production of three major feedstock commodities, maize, sugar cane, and oilseeds across these studies. Despite the fact that all models predict positive impacts on prices and production, there are large differences among the studies. Our findings point to a number of key assumptions and structural differences that seem to jointly drive the variations we observe, across these studies. The differences among the PE models are mainly due to differences in the design of scenarios, the presence or absence of biofuel trade, and the structural way in which agricultural and energy market linkages are modeled. The differences among the GE models are likely to be driven by model assumptions on agricultural land supply, the inclusion of the byproducts, and assumptions on crude oil prices and the elasticity of substitution between petroleum and biofuels.

Introduction

The world has seen rapid growth in biofuel production in recent years. Global biofuel production has tripled from 18 billion liters in 2000 to over 62 billion liters in 2007, 90% of which was concentrated in the US, Brazil, and the EU (Coyle, 2007; OECD, 2008). Global ethanol production – dominated in growth by the US and Brazil – reached 52 billion liters in 2007 and the production of biodiesel – centered mostly within the EU – increased more than 10-fold during the same period, to more than 10 billion liters (OECD, 2008).

Correspondingly, the use of major feedstock crops for biofuel production has increased dramatically. The International Grain Council reported an overall growth in the use of cereals for ethanol production by 32% in 2007/2008 and by 41% in the US from the previous year (International Grain Council data cited in von Braun (2008)). The global use of maize for ethanol grew especially rapidly from 2004 to 2007 and used 70% of the increase in global maize production (Mitchell, 2008). Biodiesel production in 2007 accounted for 7% of the global vegetable oil supplies, and one-third of the increase in consumption from 2004 to 2007 was due to biodiesel (Mitchell, 2008). Among the largest biofuel producers, the US used 25% of its maize production for biofuels in 2007 (USDA, 2007); Brazil used 50% of its sugar cane for biofuels; and the EU used 68% of its vegetable oil production, primarily rapeseeds, for biofuels (World Bank, 2008).

The potential impact of the emergence of biofuels on food commodity prices and production has generated considerable interest in the empirical economic literature. A great deal of research has been undertaken to understand the implications for agricultural markets – both at the country-specific and international level. Generally-speaking, there are two groups of studies: backward-looking ones and forward-looking ones. The first group estimates the degree to which biofuel demand has influenced the recent food and commodity price trends based on historical data. Estimates vary widely. For instance, the USDA (2008a) believes that biofuels only accounted for 3% of the retail food price increase. In contrast, others have suggested that more than 70% of the rise in food prices was due to biofuels (Mitchell, 2008). Lipsky (2008) estimates that

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biofuels account for 70% of the maize price increase and 40% of the soybean price increase.

Unfortunately, these *ex post* estimates are difficult, if not impossible to compare. The estimates differ widely due to the fact that authors examined different time periods, used data from different price series (export, import, wholesale, and retail) and focused their attention on different types of food products (Mitchell, 2008). For example, the estimate by USDA (2008a), which is low in comparable terms, is in part because the authors only considered the impact of maize prices, directly and indirectly, on retail prices (Mitchell, 2008).

This paper focuses on the second group of studies, the forward-looking ones, which generate medium- and long-term predictions of the impacts of biofuel expansion on commodity market, using equilibrium modeling techniques. For example, US-focused studies mostly have looked at the implications of energy policy (e.g., Energy Independence and Security Act or EISA) on food and feed prices (e.g., FAPRI, 2008); EU-focused studies have frequently examined the implications of EU-directives and impact on world prices and production (e.g., Banse et al., 2008); Outside of the US and EU, other studies have sought to predict the impact on prices in the developing world (e.g., OECD-FAO, 2008), malnutrition (e.g., Rosegrant et al., 2008) and implications for poverty (e.g., Yang et al., 2009). While the consensus within the literature is that biofuel growth is likely to have at least some impact on future commodity prices, there is a considerable range in the estimates. Some studies claim strong linkages (e.g., Qiu et al., 2009). Others suggest that the linkages between biofuels and commodity prices are relatively weak (e.g., Banse et al., 2008). Studies that project the impact of future biofuel production on agricultural prices provide important guidelines for setting long-term agricultural, food security, and energy policies, as well as development agenda. Therefore, when predictions vary so much, policy makers face uncertainty about which ones to depend on. Despite the importance of this topic to policy makers, there have been few studies that have tried to reconcile the differences among these outlook studies, except Golub and Hertel (2011), Dumortier et al. (2011) and JRC (2011), which indicate that the land use change and carbon emission impacts of biofuels policies are extremely sensitive to model assumptions. The study aims to put the range of numbers regarding the impact of biofuel production on agricultural market in the literature into perspective and provide a guide to the range of assumptions and modeling techniques necessary to draw policy conclusions.

This paper reviews the results of a number of the key medium- and long-term forward-looking partial and general equilibrium models. Above all, we are interested in understanding why the predictions about the future effects of biofuels vary widely among the studies. Our study focuses on a subset of the studies—in particular, on the prices and production of three biofuel feedstock crops, maize, sugar cane and oilseeds. To reach this goal we have two specific objectives. First, we will describe the range of projections from a group of papers that are focused on forecasting prices and production of the three key biofuel feedstock crops globally as well as in different parts of the world. Second, we seek to explain the differences in the projections by examining the differences in underlying assumptions and model structures.

To meet these objectives the rest of the paper is organized as follows. In Section "Issues to consider when trying to make the studies comparable" we review a number of issues that need to be considered when trying to produce a set of studies that can be compared. In Section "Identifying differences in projected impact of biofuel growth" we compare the studies and identify the variations in their results with respect to the impact of biofuel emergence on food prices and production. In Section "Explaining the differences" we examine, in detail, the underlying assumptions and structure of the analytical approaches used in the studies and draw implications of these factors on model outcomes. Finally, in Section "Conclusions" we highlight key findings of the study and suggest future research directions.

Issues to consider when trying to make the studies comparable

Because of the broad nature of this study, we have to limit the scope of this paper. Specifically, we try to include all economic papers that are global in scale. The models in the study all use partial- and general-equilibrium trade models to track the impact of biofuels. We exclude studies that are solely focused on individual countries (e.g., Arndt et al., 2008). We also exclude science-based papers that mainly examine biofuels and the environment and climate (e.g., Utrecht University-FAO, 2008). In addition, we only consider those studies that have adequately described their modeling approaches and have included scenarios that enable the effects of the emergence of biofuels on agricultural prices and production to be isolated. Because of this, for example, we do not include Elobeid and Tokgoz (2008) or the USDA (2008b). In some cases, the model versions that are included in our review contain assumptions made specifically for the analysis and thus are not identical to the standard models that the research teams maintain. Therefore, it is important to refer to the individual studies and the specific versions of the models being used in those studies for technical modeling issues.

Based on these criteria, we review nine papers (Table 1). Specifically, we review four papers that are based on partial equilibrium (PE) modeling frameworks: (a) a paper using the Aglink-Cosimo model developed by OECD and FAO (henceforth called the *OECD model*—OECD-FAO, 2008); (b) the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) model developed by the International Food Policy Research Institute (henceforth, called the *IFPRI model*—Rosegrant, 2008; Rosegrant et al., 2008); (c) a paper using the FAPRI model that was produced by the Food and Agricultural Policy Research Institute (henceforth, the *FAPRI model*—FAPRI, 2008); and (d) the WEMAC model, version 2.0 (henceforth, called the *WEMAC model*—Benjamin and Houee-Bigot, 2008). When taken as a group, we call these four papers that use *PE modeling frameworks (or PE models)* the *PE studies*.

We also review five papers that use general equilibrium (GE) modeling frameworks (Table 1): (a) a model by the Agricultural Economics Research Institute (LEI) of Wageningen University (henceforth, the *LEITAP model*—Banse et al., 2008); (b) a model by Hertel et al. (2008—henceforth, called the *Purdue I model*); (c) a model by Taheripour et al. (2008—henceforth, called the *Purdue II model*); (d) a model produced by the Economic Research Service of the United States Department of Agriculture, or the USDA-ERS (henceforth, called the *FARM II model*—Fernandez-Cornejo et al., 2008); and (e) a model created by a consortium of researchers that is supported by the Gates Foundation (henceforth, called the *GF model*—Yang et al., 2009). When taken as a group, we call these five papers that use *GE modeling frameworks (GE models)* the *GE studies*.

In order to make the results of the studies comparable, it is necessary to make some adjustments and organize some of the studies in ways that make the inter-model comparisons as straightforward as possible. First, we organize the studies by the modeling approach taken by the authors. In particular, we examine and compare the results of PE studies and GE studies separately. These must be separated because GE models seek to account for the supply, demand and prices in the entire economy, which includes simultaneously considering multiple markets, with inputs accounted for. In contrast, PE models examine the conditions of equilibrium in an individual market or within a single sector of a national economy. When using PE models, researchers hold prices,

Table 1
Selected output studies that are included in our review.

Abbreviation of study	Model description	Reference
PE studies		
OECD model	A paper using the Aglink-Cosimo model developed by OECD and FAO	OECD-FAO (2008)
IFPRI model	The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) model developed by the International Food Policy Research Institute (IFPRI)	Rosegrant (2008) and Rosegrant et al. (2008)
FAPRI model	A paper using the FAPRI model that was produced by the Food and Agricultural Policy Research Institute.	FAPRI (2008)
WEMAC model	The WEMAC model, version 2.0	Benjamin and Houee-Bigot (2008)
GE studies		
LEITAP model	A model by the Agricultural Economics Research Institute (LEI) of Wageningen University	Banse et al. (2008)
Purdue I model	A model by the Center for Global Trade Analysis of Purdue University	Hertel et al. (2008)
Purdue II model	A model by the Center for Global Trade Analysis of Purdue University	Taheripour et al. (2008)
FARM II model	A model produced by the Economic Research Service of the United States Department of Agriculture, or the USDA-ERS	Fernandez-Cornejo et al. (2008)
GF model	A model created by a consortium of researchers that is supported by the Gates Foundation	Yang et al. (2009)

quantities demanded and the supply of other products in other markets constant. The levels of income of consumers are also constant among scenarios. Because of these differences, predictions can be systematically different between the PE studies and the GE studies. For example, as shown in Wobst (2000), PE analyses tend to overestimate the *ex ante* price effects of agricultural productivity growth and policy shocks because they ignore price transmission, imperfect substitutability and factor market linkages. In contrast, GE models capture these links and show how the benefits of agricultural productivity growth are dampened throughout the economy. Therefore, in addition to carrying out 'within-group' comparisons among all the PE or GE studies considered (i.e. looking at differences within PE or the GE model types), we also conduct a 'between-group' comparison between the PE studies and the GE studies with respect to their predictions of the impacts of biofuel emergence on agricultural prices and production.

Second, since we are interested in isolating the effects of biofuels on agricultural prices and production, we consider a "reference scenario" that is close to a no-biofuels case for each of the modeling exercises. We treat the "biofuel scenario" as the alternative scenario that allows biofuel production to emerge. By comparing predictions from the baseline (or reference) model with predictions from the biofuel scenario we are able to infer the incremental effects of biofuel growth on the prices and production of major feedstock commodities and other major agricultural commodities. As noted in Section "Explaining the differences", we compare the "reference" and "biofuel" scenarios across studies, as they are not always directly comparable among studies.

Third, the period of projection varied from study to study, ranging from 7 to 20 years. We make studies comparable by looking at the results of a particular time period, i.e., 2015, that is shared by almost all of the reviewed PE and GE studies. The only exception is the FAPRI model, which used a stochastic model and reported means across the projection period and scenarios.[1]

Finally, in organizing the results of the papers to make them comparable we need to consider differences in coverage and consistency. Not all papers report findings on the same set of outcomes (that is, price and/or production). Not all papers report the same crop-specific results. Different studies report results for different geographic areas or for different sets of countries. For example, the FAPRI and WEMAC models focus on maize-based ethanol production in the US and only report prices and production for maize. In order to fill in as many gaps as possible, in many cases we asked the teams of authors and modelers for supplemental results. In other cases, we used close substitutes (see footnotes in Tables 2 and 3). For example, since maize world production is not reported for the OECD model, we use world production of coarse grains as a substitute (C. Giner, personal communication, 2008). When reporting on the results from the Purdue I and Purdue II models, we use coarse grain prices and production instead of maize prices and production. The authors that use the LEITAP model also report cereal prices and production instead of maize prices and production. In addition, in some cases commodity grouping are not always consistent among studies. For example, the OECD model reports results for vegetable oil, which is a composite of oilseed oil (including soybean oil, rapeseed oil, and sunflower oil), separately from palm oil. In contrast, when the IFPRI model reports the results for oils, the commodity category includes all oils, including vegetable oils and palm oil.

[1] The FAPRI model simulates 500 scenarios that vary in assumptions about the weather, petroleum prices, and a range of other factors that affect the supply and demand for agricultural and biofuel products (FAPRI, 2008).

Identifying differences in projected impact of biofuel growth

Projection results of the PE studies

Table 2 shows how prices and production of maize, sugar cane and vegetable oil are expected to develop in 2015 when biofuels emerge compared to the reference scenario (that is, with no biofuels) in the four PE studies. According to the PE studies, the emergence of biofuels (relative to the reference scenario) will have a positive impact on both prices and production in 2015 (Table 2). The results from all of the models show that the prices of all commodities in our study—maize, sugar cane and vegetable oil—rise (rows 1, 3 and 5). The PE models also demonstrate the special, demand-side nature of the emergence of biofuels on agriculture. Although prices are shown to rise, they do so even though production also rises (rows 2, 4, 6 and 8). All of the models demonstrate that the expected demand for agricultural commodities that is associated with the emergence of biofuels is strong enough to lead to a rise of world maize, sugar cane and vegetable oil production as well as maize production in the US.

While all of the PE studies project upward trends in prices and production, there are differences in the magnitudes of the estimated impacts among studies. Above all, the WEMAC model consistently projects the highest effects on the prices and production of maize in 2015 (Table 2, column 4). The international maize price is expected to increase by 52.6%. The US maize producer price and production are projected to be 49.6% and 18.9% higher. In contrast, the effects estimated by the OECD, IFPRI, and FAPRI models are

Table 2
Projected impact of biofuel growth on prices and production in 2015 (%): Partial equilibrium models.

	OECD	IFPRI	FAPRI[d]	WEMAC
World				
Maize: World price	14.6	16.1	–	52.6
Maize: World production	2.9[a]	4.7	–	–
Sugar cane: World price (raw)	37.1[b]	3.4	–	–
Sugar cane: World production	7.4	1.1	–	–
Vegetable oil[c]: World price	15	0.4	–	–
Vegetable oil[c]: World production	2.6	0.1	–	–
Maize				
Maize: US producer price	–	16.1	16.2	49.6
Maize: US production	–	5.0	5.8	18.9
Projection period	2008–2017	2000–2020	2011–2017	2006–2015

[a] World production of coarse grain, instead of maize, is reported.
[b] World price of sugar, instead of sugar cane is reported.
[c] Vegetable oil, a composite of oilseed oil (soybean oil, rapeseed oil and sunflower oil) and palm oil, is reported for OECD; the oil item reported for IFPRI includes all oil products (oilseed oil, palm oil, etc.).
[d] Percentage change is reported as the average change between 2011 and 2017.

Table 3
Projected impact of biofuel growth on prices and production in 2015 (%): General equilibrium models.

	LEITAP[e]	Purdue I[f]	Purdue II	FARM II	GF
Maize: US price	4.7[a,g]	22.7[b]	14[b]	23	45.2
Maize: US production	4[a]	16.6[b]	10.8[b]	33	51.3
Sugar cane: Brazil price	1.5[c,g]	18.6	17.5	24	83.7
Sugar cane: Brazil production	4[c]	8.4	8.4	53	147.1
Oilseeds: EU price	5.5[g]	62.5	56.4	–	38.0[d]
Oilseeds: EU production	4	51.9	53.1	–	95.0[d]
Projection period	2001–2020	2006–2015	2006–2015	2004/05–2014/15	2006–2020

[a] Cereals, instead of maize, is reported.
[b] Coarse grain, instead of maize, is reported.
[c] Sugar, instead of sugar cane, is reported.
[d] Rapeseed oil, instead of oilseeds, is reported.
[e] LEITAP reports production in terms of biofuel crops globally (including grain, sugar, and oilseeds).
[f] Price values are drawn from the "no by-products" scenario of *Purdue II model.*
[g] M. Banse, personal communication, 2009.

much lower and are largely consistent with one another. For example, the estimated rise of world/US maize price by 2015 is 14.6% for the OECD model, 16.1% for the IFPRI model, and 16.2% for the FAPRI model. Maize production forecasts are equally close for the three models, ranging from 2.9% (OECD model) to 5.8% (FAPRI model). However, there are differences between the OECD and IFPRI models in the projections of sugar cane prices. The OECD model estimates that 2015 sugar cane prices (production) will be 37.1% (7.4%) higher due to biofuels, whereas the IFPRI model generates estimated rises in sugar cane prices (production) of only 3.4% (1.1%).

Projection results of the GE studies

As in the case of the PE models, the predictions from the GE models demonstrate that both prices and production of key feedstock commodities in key countries will rise with the emergence of biofuels (Table 3). Specifically, the prices of US maize (row 1), the prices of Brazil sugar cane (row 3) and the prices of EU oilseeds (row 5) all rise. At the same time the strong demand-side effect of the emergence of biofuels is clear: at the same time that prices rise, the production of US maize, Brazilian sugar cane, and EU oilseeds also rise according to the predictions of all of the models (rows 2, 4 and 6).

However, as is also found in the case of the PE models, the price and production outcomes vary considerably across different models. In fact, the ranges of production and price forecasts are even wider for the GE models. For example, differences in estimated price impacts vary from 4.7% to 45.2% for maize; 1.5% to 83.7% for sugar cane; and 5.5% to 62.5% for oilseeds (Table 3). Differences in production projections are actually larger, ranging from increases of 4.0% to 51.3% for maize; 4.0% to 147.1% for sugar cane; and 4.0% to 95.0% for oilseeds (Table 3).

Although large differences characterize the predictions, a close examination reveals distinct patterns among the findings of the GE models (Table 3). Specifically, the LEITAP model consistently predicts the lowest prices and production values (column 1). In contrast, the GF model projects the highest levels of price and production impacts, except for EU oilseeds price (column 5). The other three models are in between, but also are (relatively) clearly ranked (columns 2–4). The FARM II team most often reports the second-to-highest values. Outcomes of the Purdue I and Purdue II models fall between the other three models. The projections from the Purdue I model, however, generally projects higher prices and production than the Purdue II model, except for in the case of Brazilian sugar cane and EU oilseeds production.[2] While some GE studies that we consider include alternative biofuel scenarios to account for different macroeconomic assumptions (e.g., crude oil prices), we show what we believe are the most plausible results to be considered in the comparison analysis.

In addition to the five GE studies reviewed above, a number of other studies have also used GE modeling frameworks to project the impact of biofuel growth on prices and production. These studies are not included in our analysis because they do not have

[2] There is also a wide range of projections across crops within each model. This study, however, focuses on understanding the differences in projections among the various models.

comparable reference and biofuel scenarios. For example, Al-Riffai et al. (2010) and Laborde (2011) evaluate the impact of EU biofuel policy on agricultural production, trade, incomes and carbon emissions, using the global computable GE model, MIRAGE-Biof (Bchir et al., 2002; Decreux and Valin, 2007; Al-Riffai et al., 2010). While both studies consider the impact of the mandated target of 10% renewable energy in road transport fuels against the reference scenario of biofuel production fixed at 2008 level in the EU, Al-Riffai et al. (2010) introduce a first-generation land-using biofuels share of 5.6% in the overall EU renewable energy target of 10% for road transport fuels (by 2020) with a mix ratio of 45% for biodiesel and 55% for ethanol, whereas Laborde (2011) assumes a biofuels share of 8.6% and a mix ratio of 72% for biodiesel and 28% for ethanol based on the National Renewable Energy Action Plans. According to Laborde (2011), the price and production of sugar in Brazil will increase by 8.4% and 5.8%, respectively, whereas world price and production of sugar will increase by 0.9% and 2.6%, respectively, as a result of biofuel production under the EU target. The price of rapeseed oil will increase by 16.4% in the EU and 9.2% in the world market and the price of sunflower oil will increase by 6.7% in the EU and 4.8% globally. Timilsina et al. (2012) assess the impact of biofuel policies of all major biofuel countries on the prices and production of agricultural commodities in 2020, relative to the policy/biofuel level as of 2009, using a global dynamic computable general equilibrium (GDCGE) model (van der Mensbrugghe, 2008). The world production of sugar crops, maize, and oilseeds in 2020 is projected to increase by 8.1%, 1% and 2.4%, respectively, relative to the baseline. Correspondingly, the world price of sugar crops, maize, and oilseeds will rise by 9.2%, 1.1%, and 1.5%, respectively.

Differences between the PE and GE models

Among the reviewed studies, we find that there are several systematic differences when comparing the results from the set of PE studies and the results from the set of GE studies. We understand these differences mostly come from the structural differences between an economy-wide approach that links the market-based allocation of productive factors (like labor and capital) to the supply-side, while also allowing revenue from production or ownership of productive factors to be remunerated to households – as is the case in GE models. The GTAP-based GE models that we discuss share these general characteristics, even though the specification of factor allocation (such as land in the LEITAP model), or other allocation decisions might differ between them. The PE models, by contrast, typically omit the full endogenization of productive factors in determining supply-side shifts, and do not account for feedbacks that link the revenues and rents from production to the income that accrues to households on the consumer side of the models. Keeping these differences in mind, and the range of components that are of relevance when trying to understand the driving forces behind these results – as captured in Fig. 1 – we can now look at the differences between PE and GE models that were observed in the empirical literature.

First, the ranges of prices and production forecasts are wider for the GE studies than for the PE studies. While the average gap between the highest and lowest estimate in the PE studies is only 15.8% (the average difference of rows 1–8 in Table 2), the average gap between the highest and lowest estimate in the GE studies is 38.4% (rows 1–6 in Table 3).

Second, and perhaps more significantly, for a number of the biofuels-induced, estimated price effects, the changes are higher in the GE models than in the PE models—especially when we drop some of the ''outliers'' cases (i.e., the results of the PE-based WEMAC model and those of the GE-based LEITAP and GF models). For instance, we find lower predicted price impacts for sugar cane in the IFPRI model than in the Purdue I, Purdue II or FARM II models. In addition, there are lower predicted price impacts for oilseeds in the OECD and IFPRI PE models than in the Purdue I and Purdue II GE models. For maize, this pattern, however, is not as obvious as for sugar cane and oilseeds. Again, when dropping the three outlier models (the WEMAC, LEITAP and GF models) in the case of maize price, the average change in the price due to the emergence of biofuels for the PE models is 15.6%. This level, in fact, is not too far from the average change for GE models—19.9%. These results appear to be the opposite of Wobst (2000)'s finding that PE-based analyses tend to overestimate the price effects of shocks compared to the GE analyses. We explain the discrepancies in Section ''PE models versus GE models''.

Projection results on the land use and GHG emission effect of biofuel growth

In addition to the impact on agricultural market, releases of GHG from indirect land use change triggered by crop-based biofuels have also taken important stage in the debate over the role of biofuels in climate policy and energy security in the recent literature. For example, Hertel et al. (2010) show that factoring market-mediated responses and by-product use into the analysis of GHG releases for maize ethanol produced in the United States reduces cropland conversion by 72% from the land used for the ethanol feedstock. Consequently, the associated GHG release estimated is 27 g of carbon dioxide per megajoule per year, over 30 years of ethanol production, or roughly a quarter of the only other published estimate of releases attributable to changes in indirect land use. Golub and Hertel (2011) discuss the sensitivity of the GTAP-BIO model outcomes regarding land use change and GHG emissions to changes in key parameters and assumptions. For the analysis of implications of biofuels policies for land use and GHG emissions key elements include: energy substitution parameters, including the potential for biofuels to substitute for fossil fuels; the treatment of biofuel by-products—particularly their substitutability for other feedstuffs; the specification of global trade; the determination of land cover changes in response to increased biofuel feedstock production; and the response of crop yields—both at the intensive and extensive margins—to higher prices induced by increased demand for feedstock. Dumortier et al. (2011) assess the impact of global cropland expansion on carbon emissions and the sensitivity of those estimates to modifications in assumptions concerning idle cropland, the degree of refinement in carbon coefficients, market responses, and yield increase. The results indicate that the impact of cropland expansion on carbon emissions is extremely sensitive to model assumptions. This is particularly true with respect to the price-induced yield response. Given the available knowledge, it is very difficult to narrow the range of reasonable parameter values to tighten the set of results to a level that would allow robust policy conclusions. The synthesis report by the Joint Research Centre (JRC) of the European Commission (JRC, 2011), which is based on the outcomes of an expert consultation organized in November, 2010, notes the wide differences among the PE and GE models in how land use is modeled, including assumptions about yield increases, marginal yield, by-products and pasture land effect. The report concludes that economic models tend to underestimate the long-term interconnectedness of world production and substitution between crops, because they are calibrated on short-term annual data.

Explaining the differences

This section seeks to explain some of the systematic differences in the projected biofuel impacts on agricultural prices and

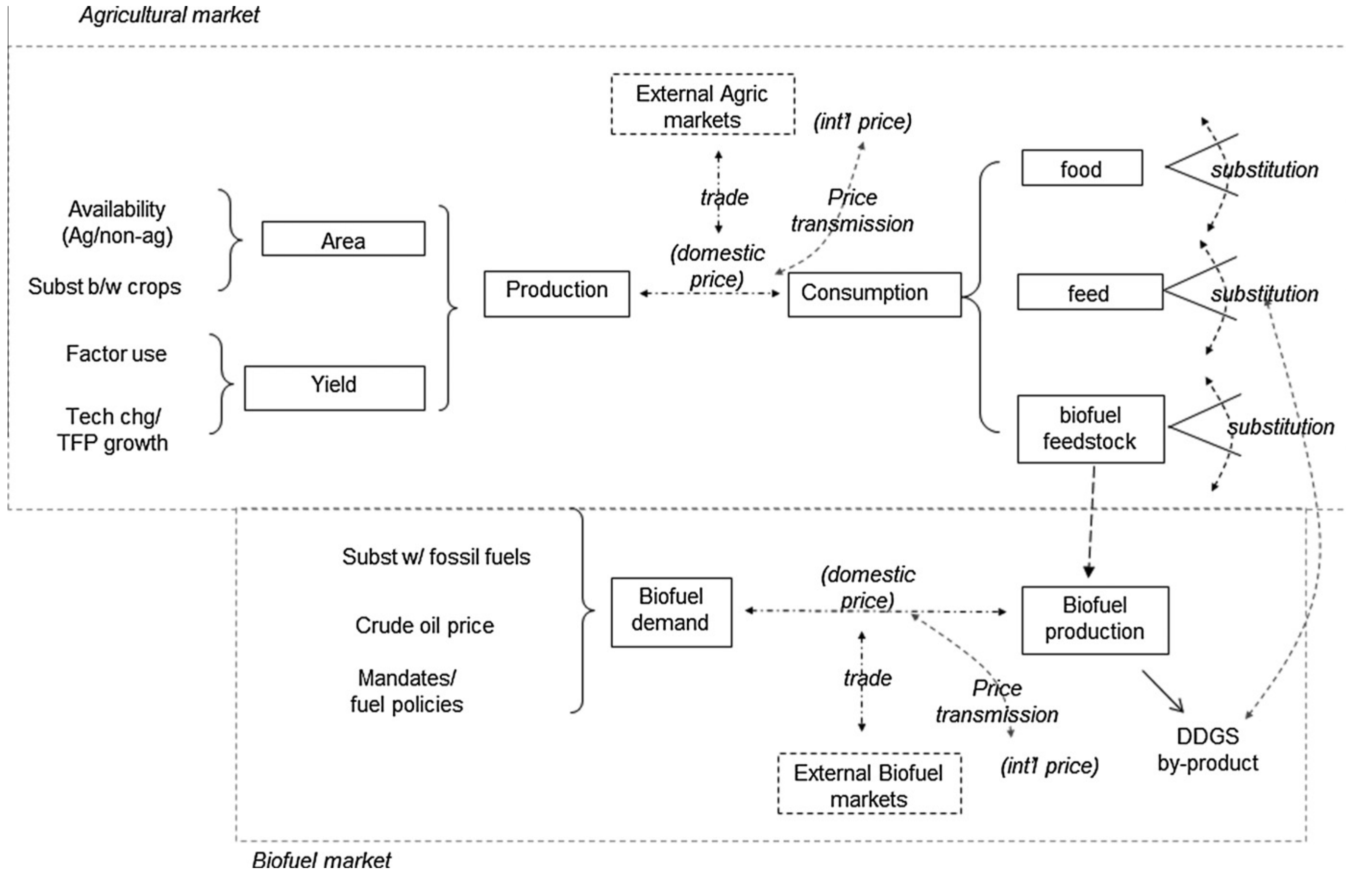

Fig. 1. Key conceptual linkages between agricultural and biofuel market dynamics.

production across the studies that were documented in the previous section. We focus on several key factors that we believe may be driving a significant share of the differences among the studies. Specifically, for the PE models, we review scenario design, key assumptions, and model structure. For the GE models, we focus on key model assumptions and parameters. Notably, the set of factors that we use to explain differences among the models differs for the PE models and the GE models. We do not include, for example, model structure for the GE models because, unlike the PE models that differ in the model representation of biofuels, most of the GE models share the standard GTAP structure (except for FARM II). Similarly, the impacts of Constant Elasticity of Transformation and Armington elasticity of substitution are not discussed, as most of the reviewed GE studies share the same assumptions. We also do not discuss in detail the effects of by-products in the context of PE models, because we do not have two-sided PE papers (one with DDG and one without) to compare.

A useful starting point for understanding the differences between the different types of models is by looking at the linkage between biofuel expansion and price changes in agricultural markets – among other effects – more broadly. A very simple framework for doing so is shown below, in terms of how the key market components of an agricultural good relates to its usage as a feedstock in the biofuel market – which has its own drivers of changes and determinants of impact. Fig. 1 shows the supply and demand equilibrium for the feedstock crop (like maize or sugar, in the case of ethanol – or a seed-based oil, as in the case of biodiesel), in relation to the supply and demand equilibrium for the biofuel product, and how the various components that determine the market dynamics of the agricultural or fuel-based good fit together. We can use this simple framework to illustrate some of the key dimensions of biofuel-driven agricultural market dynamics and how their treatment by economic market models might differ in important ways.

The response of yield to higher prices plays a key role in determining the supply-side response of the agricultural market to an increase in biofuel feedstock demand (for ethanol or biodiesel). For some models, this response might come from changes in total factor productivity (TFP) – which is a common approach used in GE models. For some models, this response might come from changes attributed to technology improvements, as is commonly done with PE models like the IMPACT model. In either case – the changes in TFP or technology are usually not explicitly endogenized with respect to market prices, and are specified as exogenous trends that can be shifted according to specific scenarios. There are dimensions of yield response that can be endogenized and modeled as a function of market prices – especially as it relates to the intensity of factor usage in production. Although many of the GE models do not model the crop-specific yields of key feedstock commodities like maize explicitly, the intensity of factor use that is employed in the production of the feedstock is often modeled within the specification of the production technologies on the supply-side. This allows the relative prices to determine how intensively factors are utilized to adjust production levels to meet changes on the demand-side of the model that might be driven by biofuels. Within PE models, like IMPACT, the yield of each feedstock crop might be represented explicitly by its own function that responds to the prices of the product – but the adjustment in the markets for productive factors like fertilizer, labor, capital and other inputs may not be fully endogenized within the model, in a way that makes the adjustment process to changing price conditions parallel to that of GE models. As expected, this would lead to differences in the way biofuel-driven increases in feedstock demand would

Table 4
Scenario design of the PE models.

	Reference scenario	Biofuel scenario	Relative level of policy-driven biofuel growth
All countries			
OECD	Biofuel production fixed at 2007 level	Policies in place in early 2008 (but no EISA); constant policies over the period to 2017	Similar
IFPRI	Biofuel production fixed at 2007 level	Policies in place by 2007 (no EISA, tax credits or tariffs)	
US-focused			
FAPRI[a]	No biofuel policies for the projection period of 2011–2017	EISA (15 billion gallons of maize-based ethanol by 2015); tax credits and tariffs extended[b]	Likely smaller than WEMAC; Inconclusive when compared to OECD and IFPRI
WEMAC	No biofuel policies for the projection period of 2006–2015	EISA (15 billion gallons of maize-based ethanol by 2015); no tax credits or tariffs	Likely largest

[a] The stochastic US model used for the analysis in the paper does not explicitly model biofuel policies of other countries, but US trade levels are calibrated to the deterministic model baseline results which reflect growing production of biofuels in Brazil and EU over time (P. Westhoff, personal communication, 2009).
[b] The US ethanol tax credit was $0.51 per gallon and the tariff on imports of ethanol from non-Caribbean countries was $0.54 per gallon in the analysis.

translate into impacts on prices and the utilization of key productive factors, like land.

Another important difference across models, and how they simulate biofuel-driven market impacts, is that relating to how important by-products of biofuel production – like dried distillers grains and solubles (DDGS) – are linked to the feed demand of biofuel feedstocks like grain or protein-based meals that are consumed by livestock. That linkage is shown within the framework illustrated by Fig. 1, and ties the supply-side of biofuels to the demand-side of the agricultural market, and the possibilities for substitution across alternative feed products for livestock. How feed substitution is modeled and how DDGS is integrated into the feed substitution possibilities is likely to differ across various models, both within the PE and GE 'families'. How the substitution between biofuel and other alternative fossil-based fuels occurs, on the demand-side of the biofuel market, will also determine how an increase in the price of oil will translate into the increase in production of a biofuel – and, therefore, its demand for an agricultural feedstock. Both the degree of fuel substitutability that is allowed within a model and the projected increase in oil prices (and how it drives biofuel demand) are important determinants of biofuel impacts on agricultural markets, and are likely to differ across models.

So with this understanding of how agricultural and biofuel markets can be linked together, we can now look more closely at the results that are coming out of the various studies that we examine – and relate their differences to the various components of our conceptual framework.

PE model-based studies

Scenario design

We begin by examining the differences in the design of scenarios among the PE studies (Table 4). Since the difference in the biofuel production levels between the reference scenario and the biofuel scenario determines the magnitude of biofuel production growth that is assumed to occur within the projection horizon of the biofuel scenario analysis, scenario design differences can lead to differences in the projected impacts of biofuel growth on the prices and production of agricultural products.

The OECD and IFPRI models have the same reference scenario ("biofuel production fixed at 2007 level") and their biofuel scenarios are similar in that, they both include policies that are in place by early 2008 with the exception of EISA provisions (Table 4).[3] The levels of biofuel production growth that are assumed to occur in the biofuel scenario analysis, therefore, are close in the two models. This may, in part, help explain the fact that projections of the OECD and IFPRI models are relatively close, especially for maize.

We see a somewhat larger difference between the outcomes of the OECD and FAPRI models, for maize, because their scenarios are designed to answer slightly different questions. In the case of the FAPRI model, the study is trying to demonstrate the impact of taking away US domestic biofuels policies, and show what happens to the levels of ethanol production and price effects. In the case of the OECD analysis, the study is more interested in explaining the global food price story, and showing what happens when biofuels are taken out of the picture, altogether.

When comparing the FAPRI and WEMAC models, the level of biofuel production growth assumed in the FAPRI model is likely to be lower than that assumed in the WEMAC model because of differences in scenario design (Table 4). On the one hand, the biofuel production level assumed in the reference scenario of the FAPRI model is likely to be higher than the level assumed in the reference scenario of the WEMAC model. This is mainly because the reference scenario of the FAPRI model assumes the absence of EISA, whereas the reference scenario of the WEMAC model assumes the absence of both EISA and the Renewable Fuel Standard (RFS).[4] On the other hand, the FAPRI and WEMAC models have similar biofuel scenarios. They both consider EISA or the production target of 15 billion gallons of maize-based ethanol by 2015 in the US. As a result of these differences in scenario design, it is not surprising to see a lower projected price impact of biofuel expansion in the FAPRI model, compared with the WEMAC model.

Crude oil price assumptions

Assumptions on crude oil prices differ across the models and may affect the impacts measured by the scenario projections (Table 5). In assessing the effect of crude oil price assumptions, we focus only on those PE studies which report those assumptions explicitly (i.e., the FAPRI and OECD models). In the OECD model, the modelers assumes that crude oil prices increase over time from $90/barrel to $104/barrel (Table 5). In the FAPRI model, by contrast, the crude oil prices decline from $87/barrel to $71/barrel. We suspect that the price impact estimated by the FAPRI and OECD models would be even closer had they used the same assumptions regarding future crude oil prices (although perhaps some

[3] EISA (Energy Independence and Security Act) sets forth a volumetric goal of 15 billion gallons of renewable fuel in 2015, which is increased annually to reach 36 billion gallons in 2020, of which 15 billion gallons must come from maize-based ethanol.

[4] The initial RFS (Renewable Fuel Standard) provision under the 2005 Energy Act specified minimum amounts of renewable fuel to be used each year, starting with 4 billion gallons in 2006 and increasing in increments of 700 million gallons each to reach 7.5 billion gallons of ethanol or bio-diesel in 2012.

Table 5
Key assumptions and model structure for the PE models.

	Land area	Crude oil price	Biofuel trade modeled?
OECD	Allow harvested area to increase	Increases from $90/barrel in 2008 to $104/barrel in 2017	Yes
IFPRI	Allow harvested area to increase	Not explicitly modeled	No
FAPRI	Allow harvested area to increase and CRP land to be withdrawn	Decline from $87/barrel in 2008 to $71/barrel in 2017	Yes
WEMAC	Allow harvested area to increase and CRP land to be withdrawn	Yes (but exact price levels not available)[a]	No?[a]

[a] Not described in detail in Benjamin and Houee-Bigot (2008).

differences might have still remained because of differences in their scenario design, and other model features).

Interestingly, the sensitivity analysis with respect to crude oil price done in the FAPRI study seems to show that higher crude oil price assumptions decrease the impact of imposing biofuel policies like tax credits and mandates on commodity prices. Specifically, under the high crude oil price scenario in the sensitivity analysis where crude oil prices are averaged at $107/barrel over the projection period, US maize price is projected to increase by 10.5% due to the EISA mandates and tax credits and tariff, much lower than the price impact projected by the low crude oil price scenario where crude oil prices fall from $87/barrel to $71/barrel over time (16.2%). While we do not expect the effect of biofuel policies to be directly influenced by crude oil price assumptions, higher crude oil prices in the baseline drive up US maize production cost considerably, leading to higher maize price. Consequently, the price change relative to baseline would be smaller in scenario with higher cruel oil prices.

Model structure

Now we consider the possible influence that differences in model structure could have on the simulated scenario results of the PE models. In this case, we are not able to fully attribute the different results to perceived differences in model structure, given the complex nature of the linkages that are involved in representing the interaction between feedstock and biofuel commodity markets. Nevertheless, there are some obvious structural differences in the way that biofuels are modeled between the OECD and IFPRI models that may affect results (Table 5).

First, despite the closeness of the maize price impact outcomes between the OECD and IFPRI models, we see a much bigger difference for sugar prices, which points to an important structural differences between those models – namely, in the way that they handle trade and the linkage between agricultural and biofuel market prices. The IFPRI model used in the Rosegrant (2008) paper does not have the biofuel trade component that the OECD study has, and is likely missing some key price-based feedbacks between feedstock commodity prices and biofuel production and export levels. This difference does not play a big part in the US maize ethanol story, however, because there is not much ethanol trade happening between the US and Brazil, anyway, due to the high tariff. In the case of sugar, however, the 'dual' nature of Brazil's sugar processing complex and how the sector interacts with sugar and ethanol exports matters a lot. Brazil has a strong connection between sugar and ethanol production and exports, given the flexible, dual-production nature of its sugar and ethanol processing facilities. In addition, the influence of Brazil on both the world sugar and ethanol markets is relatively strong, compared to other world players. It would seem, then, that any model which leaves out the price feedbacks between ethanol and sugar is likely to under-estimate the market impacts that a change in biofuel policy might have on commodity prices like sugar, which will be influenced by the endogenous production and export response of the biofuel sector within Brazil to world market conditions.

In contrast, the sugar-biofuel module allows the OECD-FAO study to simulate a diversion of sugar from food markets to ethanol production that is not replicated in the IFPRI study. The basic component of the OECD-FAO Aglink-CoSiMo model that allow this to happen is the (all-important) representation of the Brazilian sugar complex, within which there is the possibility of allocating industry output between either refined sugar for the food market or sugar-based ethanol for the fuel market, based on the relative prices between sugar and ethanol. The FAPRI model also models the interaction between sugar and ethanol markets, in a similar way. Other things being equal, this would mean that we would expect a higher world sugar price for the same increase in ethanol demand (and supply). We would also expect an impact to be felt in other commodity markets that are connected to biofuel through feedstock demand. For example, if a larger quantity of bioethanol demand is being met by Brazilian sugar cane, we would expect lower prices (or a smaller price increase) for coarse grains (which represent an alternative ethanol feedstock).

Unfortunately, we do not know for sure how the WEMAC model handles trade in ethanol between regions, and how it is linked to their agricultural markets. However, we strongly suspect that it does not have the same degree of linkage between the markets for ethanol and their agricultural markets, as the FAPRI model does, which might explain why it differs so much in terms of both world and US maize price impacts. That seems the most plausible story, given the comparison in scenario design and crude oil assumptions that we have already done.

Second, the way in which the co-products of oilseed crushing are handled in the IFPRI and OECD models is also different, with the IFPRI model not taking the effect of oilseed-based biofuel production growth on livestock feed prices into account directly, as is done in the OECD model. This, by itself, would not explain all of the differences in the projected oilseed prices shown under their scenario simulations, however.[5]

Table 5 also shows that all PE models treat land supply similarly. That is, total harvested area is allowed to change in all studies. Although the land supply assumption does not help us explain differences in outcomes among the PE models, it is useful explaining the systematic differences between the PE models and the GE models as can be seen in Section "PE models versus GE models".

GE model-based studies

Similar to the discussion above for the PE models, in this section we seek to explain some of the systematic differences among the projections from the GE models. Table 6 describes the scenario

[5] We also know that the EU oilseed-based biodiesel mandates are based on shares of transportation fuel, rather than explicit volumetric targets (as in the US case). Additionally, there is a possibility that differences can arise in the translation and interpretation of these policy mandates into the model simulations themselves, based on what is assumed as the future consumption of fossil-based transportation fuel in the EU countries (and how that is connected to future oil prices and other factors). Therefore, we are not entirely able to attribute the difference in model design and structure to the difference in biodiesel feedstock prices, without doing extensive, side-by-side model experiments and comparisons, which is beyond the scope of our paper.

Table 6
Scenario design of the GE models.

	Reference scenario	Biofuel scenario	Scope
LEITAP	No biofuel blending obligations	BFD (5.75% of renewable fuel use by 2010, 10% by 2020)[a]	EU
Purdue I	Biofuel production fixed at 2006 level	EISA (15 billion gallons of maize-based ethanol by 2015) BFD (6.25% of renewable fuel use by 2015)	US, EU
Purdue II	Same as *Purdue I model*	Same as *Purdue I model*	US, EU
FARM II	Biofuel production fixed at 2004/2005 level	EISA (15 billion gallons of maize-based ethanol by 2015)	US
GF	Biofuel production fixed at 2006 level	EISA (15 billion gallons of maize-based ethanol by 2015) BFD (5.75% of renewable fuel use by 2010, 10% by 2020)[b]	US, EU, Brazil, China

[a] The BFD (Biofuels Directive) is the key EU policy mandate promoting biofuels for transport, effective since May 2003. Targets were set for 5.75% of renewable fuel use by 2010 and 10% by 2020.
[b] Brazil and China biofuel policies are also included, but the exact policy stipulations are not stated.

Table 7
Key assumptions for the GE models.

	Total land supply fixed?	Crude oil price	DDG
LEITAP	No	Avg. annual percentage change 4%[a]	No
Purdue I	Yes	Fixed at $60/barrel (2006)[b]	No
Purdue II	Yes	Same as Purdue I model	Yes
FARM II	Yes	Fixed at $38/barrel (2004)[c]	No
GF	Yes	Increase from $62/barrel (2006) to $120/barrel (2020)	Yes

[a] Authors' calcuation (crude oil price rises by 2% to 2010 and 6% to 2020).
[b] W. Tyner, personal communication, 2009.
[c] FARM II does not report exact prices. However, since it uses the GTAP 2004 database as their baseline world economy, we approximate crude oil prices from GTAP version 7 data. $38/barrel is the world price data from IMF and the average crude oil price (average of three sport prices: Dated Brent, West Texas intermediate, and Dubai Fateh) in 2004.

design of the reviewed GE models. However, we do not focus on the issues of scenario design in the discussion of GE model-based studies, as the scenarios are similar across studies and they have relatively less explanatory power in understanding differences between model outcomes as compared to the other factors such as key model assumptions, structural features and parameter values. Although GE models are built on many assumptions and structural parameters, in this paper we necessarily limit ourselves to examining only differences in assumptions on crude oil prices, the supply of cultivated land, the ability of the model to account for important by-products of ethanol production from maize such as DDG and assumptions on the nature of the substitutability between ethanol and petroleum.

Crude oil price assumptions

The GE models make assumptions about the future trend of crude oil prices in two discrete ways (Table 7). In one set of studies, the authors fix crude oil prices at a certain level – while other models allow the crude oil prices to vary over the projection period. Among the GE models, three of them (Purdue I, Purdue II and FARM II) hold crude oil prices static during the projection period. When this occurs, the only way that the emergence of biofuels affects crop production and prices is through the policy mandates. There is no response by producers to the higher crude oil prices which might be expected to induce more production of biofuel feedstocks with subsequent effects on prices. Perhaps because of this, the three models also have the most similar predictions when comparing among all of the GE models. The price predictions also are lower than the scenarios of the GF model which assumes crude oil prices will rise.

In order to isolate the effect of crude oil prices on crop production and prices, we are able to take advantage of the sensitivity analysis included in the GF study. To examine this, we look at the differences of GF model scenarios which project production and prices when crude oil prices are fixed and when crude oil prices are allowed to rise. What is clear from this analysis is that crude oil prices themselves can have sharp effects on the prices and production of feedstock crops as well as on many other agricultural commodities. Indeed, the assumption of relatively higher future prices of crude oil is one of the key features of the GF study and may help explain why the GF projections are higher than the other GE studies.

Although the LEITAP study models crude oil prices as rising over the projection period (rising at 2% from 2001 to 2010 and 6% to 2020, which recalculates to approximately 4% to 2015), the exact levels of crude oil price assumed in the LEITAP model is not reported. It is likely that other factors are significantly dampening the effect of rising crude oil prices, if any, in the LEITAP model. In this case, we believe that the way the LEITAP model handles total agricultural land supply plays an important role in LEITAP's lowest projections among the GE models as discussed next.

Land supply assumptions

Assumptions on land supply responses are crucial for understanding the different outcomes among the reviewed studies. If land supply response is small, the increased demand for biofuel feedstock crops will have to be met by increased yields and will be limited by higher prices. Based on the reviewed GE models, land supply response is determined by two factors: the change in total land supply and the mobility among different types of land underlined by land supply structure and land substitution elasticity.

In terms of mobility among different types of land, all the reviewed GE models have attempted to capture the feasibility of shifting cultivated area from one crop to another. Purdue I, Purdue II and FARM II assume that land is mobile across uses within an agro-ecological zone (AEZ), but immobile across the AEZs. A two-level nested Constant Elasticity of Transformation (CET) function is used to represent the optimal allocation of a given parcel of land in Purdue I and Purdue II. Both LEITAP and GF models follow the land-usage structure of OECD Policy Evaluation Model (PEM) model (OECD, 2003). A three-level and four-level nested CET function are used in the LEITAP and GF studies, respectively, to allow for different degrees of substitutability among cultivated land for different crops.

As shown in Table 7, only in the LEITAP study that the total land supply is allowed to expand along an embedded land supply curve, where total land supply is determined endogenously depending on land rental rates in each region. Total land supply is fixed, however, in the other reviewed GE studies. Assumptions about the productivity of marginal land brought into production when cropland expands can also influence crop prices (JRC, 2011). However, we do not discuss in detail the effects of these assumptions. The LEITAP study does not distinguish marginal land from the existing cropland and the productivity of expanded land is thus not different from that of existing cropland. This implies that the LEITAP study is likely to overestimate the response of feedstock crop production to price increases and thus underestimate the impacts of biofuels growth on food prices.

Based on the observation that most other factors do not appear to account for the different outcomes between the LEITAP model and the rest GE models, it appears that the total land supply assumption in the LEITAP model is likely responsible for the substantially lower price effects projected by the LEITAP model than the other GE models. If this is the case, it implies that the modeling of total land supply is a crucial factor. More generally, if true, these findings also suggest that biofuels may actually have a smaller impact on food prices than some current projections show, and thus posing less of a cause of concern from the standpoint of those agents that get hurt by higher prices.[6]

Assumptions on the use of maize ethanol by-products

With the exception of one GE model (the Purdue II model), the use of DDG is not accounted for by the GE models (Table 7). According to Taheripour et al. (2008), the Purdue II model explicitly accounts for the value of by-products by incorporating them as separate commodity groupings (and also splitting sales accordingly). In this way, they allow for the substitution of DDG for animal feed. A priori, Taheripour et al. (2008) argue that when models ignore DDG they may be overestimating the impacts of biofuels, since although biofuels drives up demand for feedstock crops, the industry also increases the supply of an alternative animal feed that can at least in part offset the price-rise effect.

The effect of including DDG in the modeling framework when looking at the impact of the emergence of biofuels on the prices and production can be seen by comparing the results of the Purdue I and Purdue II models. Specifically, the Purdue II model reports lower projections than the Purdue I model. Conveniently, the two models differ only by the inclusion of DDG, which clearly indicates that accounting for DDG dampens the projected effects of biofuels on the prices and production of feedstock crops, especially for maize. This suggests that the consideration for the by-products of biofuel production is an important step in all modeling effort, in order to avoid overstating the results for price and production effects – especially for maize. It also appears to be part of the reason that, with the exception of the LEITAP model, the projected rises in the prices and production of biofuel feedstock crops are lowest for the Purdue II model.

Elasticity of substitution between petroleum and biofuels

Another factor that may affect the results from the different models is the assumption concerning the degree of substitutability between petroleum and biofuels. If petroleum and biofuels are highly substitutable, then when the price of petroleum rises (or when any factor that affects oil demand changes), we would expect a strong effect on biofuels. If, however, petroleum and biofuels are less substitutable (or are complements), then there will be less of a link between crude oil prices and the emergence of biofuels.

In order to further understand the differences in the assumption on the elasticity of substitution between petroleum and biofuels, it is helpful to understand the complexity involved in determining accurate substitution elasticity values. Whether biofuels and gasoline are substitutes or complements is a critical determining factor, which is closely linked to technological, policy, market and infrastructural issues that influence the relative value of energy sources. For example, technological developments largely determine flexible-fuel vehicles as alternative energy vehicles that can run on either hydrated ethanol (ethanol as a substitute), gasohol mixtures (combining gasoline and anhydrous ethanol, or ethanol as a complement), or any blend ratio between gasoline and ethanol, as in the case of Brazil. In addition, the substitutability of biofuels and gasoline is contingent upon the feasibility and availability of infrastructural developments necessary for large-scale adoption of biofuels, which includes the logistical factors for transporting, storing (for example, pipelines and gas stations in the US are largely for gasoline and not ethanol), and retailing of ethanol since they determine whether consumers have access to E-85 pumps. Dual-processing plants, such as those in Brazil, can interchangeably produce ethanol and sugar, allowing for increased flexibility to alternate production based on market prices (Elobeid and Tokgoz, 2006). Production can shift 60% in either direction so prices of ethanol and sugar are closely tied together in Brazil (Elobeid and Tokgoz, 2006).

The assumption on the elasticity of substitution between petroleum and biofuels appears to have a large role in explaining the high projections of the GF model (Table 8). In three of the GE models, the LEITAP and the two Purdue models, the modelers make similar assumptions on the elasticity, using values ranging from 1.0 to 3.95. These elasticities are considered quite low and imply little substitutability between petroleum and biofuels. In contrast, the GF study makes a fundamentally different set of assumptions with their elasticity of substitution set at 10, a level that suggests gasoline and ethanol will be highly substitutable by 2015. Since this is one assumption that sets the GF study apart from the other models, the high GF projections are likely to be at least in part related to their decision to assume that petroleum and biofuels will be highly substitutable in the future. Sensitivity analysis in their paper supports this conclusion. When the analysis moves from a high elasticity scenario to a low elasticity of substitution scenario, the projected impact of biofuels on the prices and production of, maize, for example, falls sharply. If the impact of biofuels is as sensitive to substitution elasticity as the GF model results suggest, this points to both the need and importance of being able to accurately predict elasticities in the near future.

PE models versus GE models

The discussion above has focused on explaining the differences among the PE models and among the GE models. In this subsection we seek to understand the effects of choosing between a PE framework and a GE framework. As can be seen above, we observe much wider ranges of differences in projection outcomes across reviewed GE models than PE models, which may be somewhat surprising given the common ancestry of all the GE models we review (they are all GTAP-based, except for FARM II). This is likely due to the use of two important assumptions (or modeling decisions) by the LEITAP and GF models. Specifically, it appears as if the inclusion of the land supply function in the LEITAP model has driven down the projected

Table 8
Elasticity of substitution between petroleum and biofuels for the GE models.

	LEITAP[a]	Purdue I	Purdue II	FARM II[b]	GF[c]
US	3.0	3.95	3.95	–	10
EU	2.75	1.65	1.65	–	10
Brazil	1.0	1.35	1.35	–	10
Other Regions	–	2.0	2.0	–	10

[a] Elasticities of substitution between petroleum and biofuels.
[b] No elasticities of substitution between petroleum and biofuels.
[c] Reference scenario has low elasticity of 3 for all geographic regions. Elasticities between ethanol and gasoline.

[6] This land supply effect may, however, be a cause of concern from the standpoint of greenhouse gas (GHG) emission associated with biofuel production, as indirect land use change has been shown to potentially undermine the ability of biofuels to deliver on potential GHG emission savings.

impacts of biofuels on the prices and production of feedstock crops, a modeling feature used by none of the other studies. Likewise, it appears as if the assumption of high elasticity of substitution between gasoline and biofuels, accompanied by the assumption of high crude oil price by the GF model has led to its relatively high projection outcomes. Once these two outliers are accounted for, the outcomes of the other three GE models are fairly consistent.

In general, we would expect to see higher price impacts in the PE models than the GE models, because the PE models lack the inter-sectoral feedback effects and impose fixed factor price assumptions that exacerbate the price shock effects. Interestingly, this is not consistent with our findings—at least in the case of some commodities as discussed in Section ''Differences between the PE and GE models''. While it is difficult to single out the exact determinants of such inconsistencies, for a broad study like ours, we believe that a confluence of factors may play a role in producing the results we observe.

For sugar cane price and production, the results of the IFPRI model are smaller than those of the GE models (excluding the outlying cases, the PE-based WEMAC model and the GE-based LEITAP and GF models). This suggests that some of the factors that contribute to the differences between the IFPRI model and the OECD model as discussed in Section ''PE model-based studies'' might also be playing a role here. Among these are the way in which ethanol and sugar trade are linked, especially for key countries like Brazil, and the degree to which complex sugar policies (such as tariff rate quotas) are represented in the models. The GE models represent trade as bilateral flows, to capture the specificity of tariff barriers between countries, whereas the IFPRI model (like some other PE models) represents trade in terms of total net exports and imports where countries import from and export to a pool of demand/supply representing the rest of the world, and might miss some of the specificity in bilateral policy, which is quite complex in the case of sugar. The world sugar model that the OECD model uses is able to capture this complexity in a better way, which may explain why their results are closer to the non-outlier GE model results.

Furthermore, the PE and GE model differ in their ability to model the substitutability between crude oil and biofuels in all sectors, including the transport sector. The PE models treat crude oil as an exogenously specified driver, with no other modeling of the fuel sector being done. Since the feedbacks that determine the overall demand for energy by the transport sector are likely missing in the PE models, we would also expect for there to be divergence between the PE and GE model results.

There are other more general ways in which the PE models differ from the GE models, which might explain the divergences that we observe between their results. The key issues that distinguish the GE and PE models are the assumptions on factor mobility, the degree of perfect/imperfect substitutability of factors in production (or goods in consumption) and, most importantly, the adjustment of factor prices to policy shocks. Wobst (2000) illustrates the importance of factor price fixity in explaining some of the major differences in simulated policy shocks between the PE and GE models. In his case, the author looks at a single country (Tanzania) and modifies a standard GE model to reflect the perfect substitutability, factor immobility and price fixity of a PE model – while still preserving some of the income feedbacks and economy-wide multiplier effects that the existing social accounting framework provides.[7] For the policy experiments that were simulated, Wobst (2000) shows that the GE/PE model (where ''GE/PE'' refers to the restrictions imposed on the GE model that make it behave like a PE model) shows larger price effects compared to the GE model, due mainly to the fixed factor price assumption. This is consistent to what we observe with the OECD model results, relative to the GE model results for sugar cane, as well as for the WEMAC model results for US maize, compared to those of the Purdue I, Purdue II, and FARM II models. In other cases, however, the GE model results seem larger than some of the PE model results (for example, the oilseeds price and production effects for the Purdue GE models relative to the IFPRI and OECD PE models, and the FARM II and Purdue-I GE model results for US maize, relative to the FAPRI and IFPRI PE model results). Given the fact that Wobst (2000) only did his experiments for a single-country model, compared to the global level models that we are discussing here, and that his modified GE/PE model still contains full-income and economy-wide multiplier effects that are missing from most PE models, his conclusions may not carry over universally to all cases and types of policy shocks.

Finally, we note that the PE models are also fairly flexible in their ability to expand their harvested area, compared to the structure of most GE models that treat land as a sluggish factor with small mobility among different types of land and thereby restrict the expansion of crop land (except in the case of LEITAP). Therefore the price impacts might be further dampened in the PE models, relative to the GE models for certain cases.

Conclusions

Biofuels production and distribution are extremely complex processes involving markets for land, crops, livestock, energy and food (Golub and Hertel, 2011). The predicted impact of increased biofuels production depends on the model assumptions about the economic structure and parameters governing each of these processes (Golub and Hertel, 2011). This study undertakes an in-depth review of some key outlook studies which quantify the impacts of biofuels on agriculture, and which are based on either general-equilibrium (GE) or partial-equilibrium (PE) modeling approaches. We attempt to reconcile the systematic differences in the estimated impacts of biofuel production growth on the prospective prices and production of three major feedstock commodities, maize, sugar cane, and oilseeds across these studies, with the range of assumptions and model characteristics that are embedded within them.

Overall, all outlook studies reviewed indicate that biofuel growth will lead to higher prices and production levels for the three primary feedstock crops of 1st generation biofuels by 2015. In other words, all modeling efforts believe that—to a greater or lesser extent—biofuel development is likely to remain an important driving force in world agricultural markets over the medium term. Since most of these basic results are driven by comparing the baseline of 'no-biofuels' with an alternative scenario which allows the policy-driven emergence of biofuels, the impacts of ambitious policy objectives in major biofuels-producing countries are shown to be significant and uniformly consistent, as to the *direction* of the simulated effects.

Despite the fact that all models predict positive impacts on prices and production, there are large differences among the studies. Our findings point to a number of key assumptions and structural differences in the modeling approach that seem to jointly drive the variation we observe, across these studies – some being related to particular assumptions or behavioral specifications built into individual models, and some being more systematic across broader classes of models, such as the partial (PE) or general-equilibrium (GE) models. First, the scenario design – and the underlying assumptions of biofuel policy, market penetration,

[7] The multiplier effects that we refer to, here, are those which arise from the social accounting framework that Wobst (2000) maintains in his modified GE model, which allows the shocks in one part of the economy to propagate themselves through the linkages that exist with other sectors. So an increase in tourism activities might translate to higher incomes for rural and urban households, for example, which will stimulate growth in demand for agricultural and non-agricultural consumption goods, and lead to other second-round effects.

etc. – appears to be an important factor for the PE models and has likely contributed to relatively high price impact of biofuels in the WEMAC projections. Second, the presence or absence of biofuel trade, and the structural way in which agriculture and energy market linkages are modeled, are likely to account for some of the differences we see between models within the PE class, such as the OECD and IFPRI model projections for sugar and vegetable oil. Third, relaxing restrictions on total agricultural land supply may be the driving force for LEITAP's relatively low estimate of price impacts, relative to the other GE-based projections. Fourth, accounting for the possible contribution of DDG by-products to animal feed is the distinguishing difference between the GTAP-based Purdue I and Purdue II models – and also extends to models within the PE family that account for those effects such as the FAPRI and OECD-FAO models and those that do not, such as the IMPACT model. Fifth, the high degree of substitutability between petroleum and biofuels (especially when combined with assumptions on future crude oil prices) is the distinguishing feature of the GF study and contributes towards its relatively high predictions on price and production impacts, relative to other GE models. The assumption—whether true or false—relates closely to what is envisioned in terms of future technology adoption within the transportation sector. Policy and economic factors will weigh in heavily on determining which types of the flexible-fuel vehicles will become widely available and also the types of fuel sold at filling stations. For example, if policies are slow to encourage the adoption of flexible-fuel vehicles or impose 'blending walls' such as those which exist in some regions of the US, then the degree to which biofuels are substitutable with gasoline and diesel may be limited.[8] Furthermore, if biofuels are sold at or below their energy values with respect to gasoline and diesel, there will be enough consumer demand to encourage the building of E-85 or other alternative fuel pumps. Because these differences in assumptions make a significant difference, policy makers should take into account the underlying assumption-based and structural differences among models when using model-generated outcomes to evaluate economic and environmental impacts, and to guide decision-making.

Based on our findings, we have identified a number of urgent knowledge gaps and uncertainties that need to be addressed by future research. First, there is a need to learn more about key model parameters such as the elasticity of substitution between oil-based fuels and biofuels because of their importance in driving GE model results. Knowledge on these parameters is extremely limited, so far, especially with regard to how they might evolve over time, given that their values are often set based on calibration to a relatively short series of historical data or by expert judgment. Second, better predictions of future crude oil prices are needed for both PE- and GE-based studies, ideally, in the same way that IPCC harmonizes the assumptions underlying quantitative assessments of future climate change impacts, and examines the model-based sensitivity and other key sources of uncertainty that are embodied in the wide range of scenario results. Third, the future expandability of agricultural land supply and the contribution that by-products of biofuel production can make to livestock feed balances are likely to be crucial factors that determine the price impacts of model-based projections, and should be carefully studied. Fourth, the on-going research that is being undertaken by various groups in projecting long-term biofuel impacts on agriculture can benefit greatly from more coordinated modeling efforts, so as to improve the sharing of knowledge and generate a better understanding of the key factors that may offset or aggravate the effects that biofuels can have on market dynamics, environmental quality and, ultimately, human welfare. The lesson for policymakers is that results from economic models depend heavily on assumptions, and because we are trying to predict long-run human behavior, legitimate differences can be present in those assumptions (Dumortier et al., 2011).

[8] There are also arguments that gasoline and biofuels will not be easily substituted in the future. For example, technological advancements may not enable flexible-fuel vehicles to be competitive in terms of either cost or efficiency when compared to traditional vehicles.

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Appendix A. Supplementary material

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