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Market-mediated environmental impacts of biofuels ☆

Thomas W. Hertel [a,*], Wallace E. Tyner [a]

[a] Purdue University, USA

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ABSTRACT

This paper surveys the evidence on market-mediated environmental impacts of biofuels, with special attention to the indirect greenhouse gas emissions stemming from land cover change in the wake of increased demand for biofuel feedstocks. We find clear evidence that market mediated land use response to crop price changes has occurred over the past decade. However, despite all the research that has been done and all the advances made, there remains considerable quantitative uncertainty surrounding biofuels induced land use change. Obtaining precise estimates of these impacts is likely beyond the reach of current models and data.

1. Background and policy context

The global leaders in biofuel production have been the US, Brazil, and the European Union (EU) (Tyner, 2008). In all three regions, the initial policies used to stimulate biofuels were government subsidies. However, over time as the level of biofuels production grew, and the burden of the subsidy on government budgets increased, all three regions moved towards mandates or targets, which shift the cost of the policies towards consumers of the biofuels. The major biofuel in the US and Brazil is ethanol, and in the EU, it is biodiesel. The first major push for US ethanol was included in the National Energy Conservation Policy Act of 1978 (U.S. Congress 1978). It provided a subsidy of 40 cents per gallon of ethanol. The ethanol subsidy ranged between 40 and 60 cents per gallon between 1979 and 2011, when it ended. A subsidy for biodiesel also was added, which still exists in 2013.

The next major change was the creation of the Renewable Fuel Standard (RFS) in 2005 and its expansion in 2007 (U.S. Congress 2005; U.S. Congress, 2007). The RFS mandates a total of 35 billion gallons ethanol equivalent of different types of biofuels plus 1 billion gallons of biodiesel. Of that up to 15 billion gallons can be met with corn ethanol. Today about 40 percent of US corn (27 percent after accounting for the byproduct credit) goes into corn ethanol.

The biggest issue faced by the ethanol industry today is what is called the blend wall (Tyner and Viteri, 2010; Tyner et al., 2010). This effectively limits the ethanol blend in US gasoline to 10 percent. Since total US gasoline type fuel consumption is 133 billion gallons, the blend limit is about 13.3 billion gallons. However, the 2013 RFS level is 13.8 billion gallons—more than the amount that can be physically blended. This poses a significant challenge to the industry.

From the early days of biofuels, their environmental benefits have been touted as an important advantage over fossil fuels (Tyner, 2008). Biofuels were believed to reduce direct emissions from automobile fuel consumption and to reduce life cycle greenhouse gas (GHG) emissions due to the renewable nature of the feedstocks used (Farrell et al., 2006). Direct emissions are calculated based upon the emissions associated with the growth of the biomass feedstock, transportation to a processing facility, emissions from the conversion to a biofuel, and emissions connected with the transport and distribution of the biofuel to the ultimate automobile consumer. In this context, direct emissions are sometimes characterized as 'field to wheel', analogous to the 'well to wheel' measures for fossil fuels. In the U.S., most estimates of direct emissions are done using the GREET model developed at Argonne National Laboratory (Wang, 1999). GREET comprises all emissions associated with feedstock production including fertilizer, planting, chemical applications, harvest, etc., and estimates the efficiency of conversion of the biomass material to biofuels. Most of the direct emission estimates conclude burning a mega joule worth of corn based ethanol produces less GHG emissions than getting the same amount of energy from fossil fuels.

As more research has been done on environmental impacts of biofuels, it has become clear that some of the early promise of

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* Corresponding author. Tel.: +1 765 494 4199.
E-mail address: hertel@purdue.edu (T.W. Hertel).

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reduced emissions has not been fulfilled. One of the largest sources of potential GHG emissions associated with biofuels results from the indirect land use change (iLUC) induced by the biofuels-augmented demand for feedstock. We call this a *market-mediated response* and it will be the focal point of this survey. iLUC can be illustrated with the case of corn ethanol produced in the US, which has now surpassed corn fed to animals—previously the pre-dominant use of US corn. When government support encourages more use of corn for ethanol, ethanol producers must outbid current buyers using it for feed and food. All else equal, this will lead to an increase in the price of corn. Due to the higher price, there will be more corn grown to satisfy the enlarged demand. This additional corn production can come from intensification on existing corn land, crop switching to allow for more corn area, and/or from conversion of pasture or forest to cropland. It is this latter possibility that we call induced land use change. It causes GHG emissions because when land cover is converted, stored carbon in the wood or pasture is released by fire or decay and also an opportunity to store additional carbon in the future is sometimes foregone. The increase in emissions due to this iLUC is added to the direct emissions to get total GHG emissions for the biofuel.

The possibility of iLUC-related emissions was first raised in the seminal work of Searchinger, et al., who estimated that corn ethanol actually increases GHG emissions, relative to gasoline (Searchinger et al., 2008). Since this original study, many other analyses have been published, generally finding much lower indirect GHG emissions, thereby suggesting a more nuanced picture (Tyner and Taheripour, 2012; Wang et al., 2011; Hertel et al., 2010). In addition, other environmental impacts of biofuels have now been considered in greater detail (National Research Council, 2011). Most of these early studies relied heavily on simulation models because there was too little production of biofuels to see actual land use change globally. The absence of empirical evidence behind these assertions of market-mediated effects stemming from the biofuels programs led to justifiable skepticism on the part of some industry supporters (Kim and Dale, 2011). However, the Kim and Dale data analysis ended in 2007, before the major biofuels boom, and this work has been criticized on other grounds as well (O'Hare et al., 2011).

In recent years, biofuel production has increased substantially, especially in the US and Brazil. And, when coupled with other factors, including growth in developing countries and the associated dietary upgrading, we can now see the expected results: (i) significant world price increases (Abbott et al., 2008; Abbott et al., 2011) and (ii) global crop harvested area expansion as shown in Fig. 1. During the period of the 'biofuels boom', 2006—2011, we see that global harvested area for major field crops rose by 42 million hectares. Furthermore, as shown in Fig. 2, a large share of these increases have come in crops which are used in biofuels (corn, oilseeds), and the land cover change has been global in scope (Fig. 3)—suggesting that the transmission of these price signals through world markets is indeed an effective means of stimulating land use change.

Clearly, there have been many other drivers of changes in agricultural commodity prices and cropland expansion beyond biofuels (Abbott et al., 2008, 2011; Timmer 2008; Trostle et al. 2011). In 2011, Abbott, Hurt and Tyner indicate that the largest drivers of commodity price increases were biofuels and Chinese demand for soybean imports (Abbott, Hurt et al., 2011). However, regardless of the source of US corn price change, the impact on international land use is evident. Indeed, Villoria and Hertel (2011) estimate a statistical model which relates international changes in coarse grains area harvested to changes in US corn prices, while

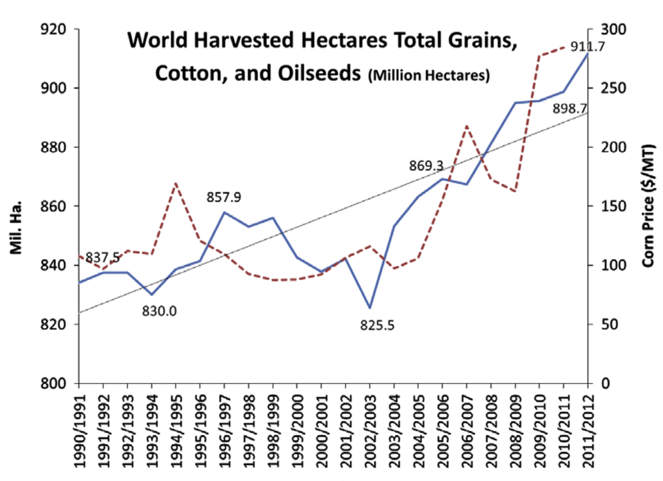

Fig. 1. Global harvested area for grains, cotton and oilseeds (solid line) and corn price (dotted line) for crop years from 1980/81—2010—2010/2011.
Source: USDA, WASDE, and USDA feed grains data base.

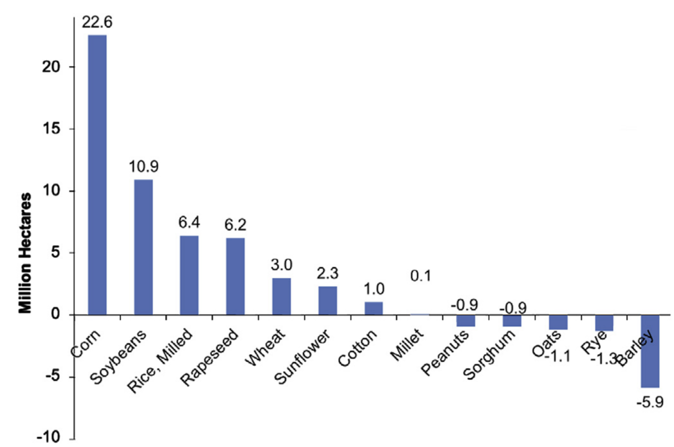

Fig. 2. Change in World Harvested Area, by crop, 2011/12—2005/06 (positive number corresponds to a rise in harvested area for a given crop).
Source: USDA WASDE

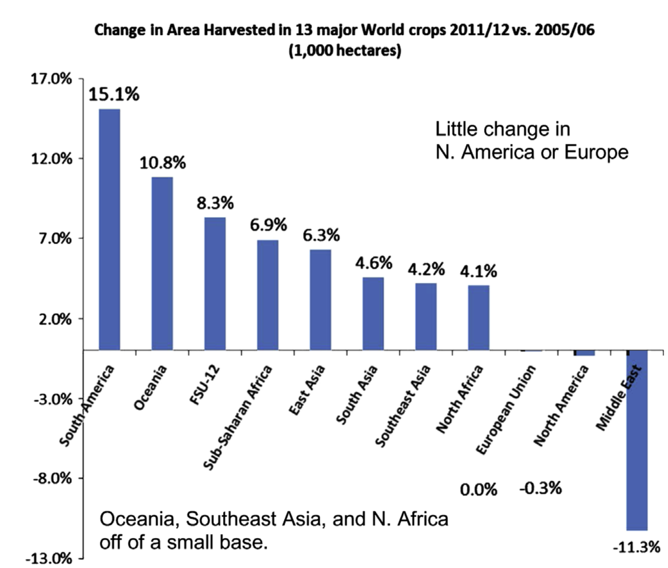

Fig. 3. Change in Harvested Area by Region (million hectares) for the 13 crops reported in Fig. 1. Results reported as the difference: 2011/12—2005—2005/6 crop years. A positive number indicates a rise in harvested area for that region.
Source: USDA WASDE

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controlling for other factors. They find a strong relationship—and one which is shaped by existing bilateral patterns of trade.

In addition to agricultural prices, there are other market responses to biofuels expansion that need to be considered. For example there are potential impacts on the prices of crude oil and petroleum product prices resulting from biofuels production. The literature on this topic generally suggests that this effect is quite small due to the fact that the energy supplied by biofuels is such a small part of the total liquid fuel market (Taheripour and Tyner, 2013; Hochman et al., 2010). Also, there is a 'rebound effect'. To the extent that crude oil prices do fall, there will be more oil consumed, which itself increases GHG emissions. Since the reason we are interested in potential emissions reductions from the substitution of biofuels for gasoline is to reduce the rate of global warming, we must bear in mind the temporal profile of GHG releases. As pointed out by O'Hare et al. (2009), iLUC emissions are particularly damaging since the added emissions from cropland conversion occur as soon as the added biofuel capacity is introduced, while the savings from gasoline displacement occur over the lifetime of the project. For any finite time horizon, the damages from early releases of long-lived emissions into the atmosphere will be greater than from later GHG emissions. To factor in this effect, O'Hare et al. (2009) suggest a new measure of fuel performance—"Fuel Warming Potential"—which compares fuels based on cumulative radiative forcing over the life of the project.

2. Market-mediated impacts of producing biofuels from foodstuffs

In this survey, we will distinguish between the market-mediated impacts of producing biofuels from foodstuffs (largely first generation biofuels), and those stemming from the production of biofuels from cellulosic feedstocks, which may compete less directly with the food system. There is more evidence available on the former and so we begin with this topic. Most of the literature to date on the market-mediated effects of biofuels has focused on energy produced from products which would otherwise be destined for food consumption, either directly or indirectly (e.g., livestock feed). Therefore, for a given level of global food consumption, removal of agricultural products for use as bioenergy feedstock will require additional production at the same location, or, in light of global agricultural trade, somewhere else in the world. Commodity prices are the market mechanism through which the signal to generate additional farm output is conveyed to producers. And economists spend a good deal of effort measuring these responses over both the short and long run, summarizing their findings in terms of unit-free, price elasticities of supply and demand which capture the percentage quantity response to a one percent increase in prices. In this section we will focus on three key margins of economic response to biofuel-induced scarcity (Hertel 2011). The first is the extensive margin of supply response, or the percentage change in production obtained from area expansion. The second is the intensive margin of supply response, which measures the potential for producers to increase yields on existing land through more intensive cultivation. The (negative) response of agricultural product demand to rising prices (e.g., people eating less meat) is the third key margin of economic response. The more demand responds to price, the less response is required on the supply side to accommodate the increase in biofuel demand.

2.1. *Extensive margin of supply response*

During the ethanol boom in the US, at the beginning of this century, US corn harvested area rose sharply, from about 70 million acres in 2001 to a peak of 87 million acres in 2007 (US Department of Agriculture, National Agricultural Statistics Services, 2012). This offers clear evidence of the supply responsiveness of agriculture at the extensive margin. Of course, this new corn area had to come from somewhere, and most of it came from soybeans, whose harvested area over the same period fell from 74 to 65 million acres (US Department of Agriculture, National Agricultural Statistics Services, 2012). Reduced area in the US contributed to higher soybean prices, which in turn encouraged additional production in many parts of the world—particularly South America, which is quite responsive to developments in the US market (Villoria and Hertel, 2011). In this way, a price increase for corn in the US is transmitted to other countries and commodities and contributes to a general rise in the price of field crops worldwide.

With prices for crops rising, there is an incentive for overall expansion of harvested area, and this was indeed the case over 2000—2010, as shown in Fig. 1. From the standpoint of climate impact, the critical question is: where does this expansion occur? Does it translate into cropland cover expansion? If so, and if it arises in carbon rich environments, then there is greater potential for environmental damage through GHG emissions. Biodiversity loss can also result from such cropland conversion. If, in addition, the land which is converted has relatively low yields, then more conversion is required to meet the global shortfall. West et al. (2010) evaluate the ratio of carbon loss from cropland conversion to current agricultural yields around the world, and find that it is particularly high in the tropics, suggesting that induced land use change in that region is likely to carry with it a particularly high environmental cost. This is of special concern, given the geographic profile of harvested area change over the last decade (Fig. 3).

Absent other available information, the earliest study of global land use impacts of biofuels (Searchinger et al., 2008) used a simple historical rule of thumb to determine the likely compositional impact of cropland conversion, based land cover change at continental scale from 1990—2000. A more highly resolved approach to analysis of land use change is that of Gibbs et al. (2010) who drew on observations at specific sites throughout the tropics sampled over the period from 1980—2000. A striking finding of their study is that 55% of the sampled sites which had been converted to cropland over this period had been in closed forest at the start of the period. Of course, both of these historical case studies are limited in that they do not control for other variables of interest. A more sophisticated study of land cover change is offered by Lubowski et al. (2006) who make use of site-specific USDA-NRI data over two decades to estimate a model of land cover transitions in which the individual transition probabilities depend on the relative returns to land use in the different types of cover. These estimates show that US pasture is far more responsive to changes in cropland returns than is forest cover—a finding that is important from the standpoint of limiting carbon emissions from cropland expansion, as conversion from pasture results in much smaller carbon fluxes (Plevin et al., 2011).

Given the limited time series data availability at global scale, virtually all studies of market-mediated land use change stemming from biofuels rely on simulation models. One of the more popular types of models for determining the market-mediated effects of biofuels is the class of Computable General Equilibrium (CGE) models (Al-Riffai, Dimaranan, and Laborde, 2010; Banse et al., 2008; Hertel et al., 2010; Taheripour et al., 2010), which explicitly disaggregate land—often by Agro-Ecological Zone (AEZ) (Ramankutty et al., 2005). In this context, expansion of cropland displaces the competing land cover types which are found in the same AEZs as the feedstocks or their close substitutes.

A critical factor in determining the amount of land which must be converted following an expansion of biofuels production is the productivity of the newly converted land, relative to existing

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cropland. From a narrow economic point of view, the presumption is that land in the same general region, but not currently under crops, would be less productive—otherwise it would already be under cultivation by profit-seeking producers. However, that need not be the case if there are other barriers to bringing the land into crop production, or if additional investments are required which may then bring that land up to the average productivity level of other land in that Agro-Ecological Zone. The latter is the case in the Brazilian Cerrado, where very significant investments in land improvements are required before planting soybeans, but once these improvements have been made, soybean yields on the newly converted lands are comparable to those on existing cultivated hectares (Deininger and Byerlee 2010).

Estimating the relative productivity of marginal land for each region of the world is clearly a large task. The early work of Searchinger et al. (2008) abstracted from this aspect of the iLUC problem, assuming instead that any reduction in average yield due to area expansion would be offset by intensification of production —another margin ignored by that early study. The subsequent paper by Hertel et al. (2010) used an estimate 0.66 as the ratio of productivity of marginal lands relative to average productivity, based on unpublished data on land idled under the US Conservation Reserve Program. Taheripour et al. (2012) have refined the estimates of the productivity of marginal lands using the Terrestial Ecosystem Model (TEM) to estimate relative productivity of non-cropland to cropland at the grid cell level, thereupon aggregating to global AEZs. Using these more disaggregated estimates of the productivity of marginal land instead of the previous globally uniform value, they find that the land requirement for U.S. biofuel mandates is 25 percent lower than previous estimates.

An important determinant of the productivity of newly converted cropland is access to adequate water—either through precipitation or irrigation. By grouping land endowments into agro-ecological zones, the models used to analyze iLUC implicitly account for rainfall, as this is one of the key criteria in defining AEZs. Irrigation, on the other hand, has generally not been well-handled in studies of iLUC flowing from biofuels expansion. By ignoring the distinction between rainfed and irrigated lands, most authors implicitly assume that the two expand (or contract) in equal proportions. However, this is unlikely to be true in many regions of the world. Water availability is already a constraining factor in many parts of the world, and these deficits are expected to become more severe in the future (Rosegrant et al., 2013).

In an effort to understand how such irrigation constraints affect the pattern of land use change following biofuels expansion, Taheripour et al. (2013) modify the GTAP-AEZ-BIO CGE model used for iLUC analysis in order to incorporate the rainfed-irrigation distinction. They then simulate the global land use and emissions impacts of US corn ethanol expansion under a scenario in which irrigation expansion is not permitted in regions identified by the International Water Management Institute as experiencing physical water scarcity. The authors contrast this pattern of iLUC and GHG emissions with that arising from a more traditional approach in which the rainfed-irrigated distinction is ignored. Their conclusions are striking. With expansion constrained in some of the most high-yielding irrigated areas of the world, cropland expansion in the remaining regions must be larger. Furthermore, the pattern of water scarcity shifts iLUC away from dry regions with low carbon emissions factors towards rainfed regions with much higher carbon content. As a consequence, the authors find that previous estimates *understate* global GHG emissions associated with corn ethanol production by about 25%.

Looming over all of this discussion of the extensive margin is the question: how much land is ultimately available for conversion to agriculture? The answer to this question depends on the time horizon which one adopts, as well as the treatment of biophysical, ecological and socio-economic constraints to land conversion. Lambin et al. (2013) seek to provide a global scale estimate of potential available cropland on a 5—10 year time scale. They conduct six, detailed, bottom-up case studies in those areas of the world deemed most promising for agricultural expansion: the Chaco region of in the Southern Cone of South America, the Brazilian Cerrado, the Amazon, Congo, Indonesia and Russia. In these case studies they account for biophysical constraints — ruling out very low productivity lands, ecological constraints due to high carbon stocks or biodiversity, and socio-economic constraints — including land which is already in use and not available for conversion. With the exception of the Amazon, they come up with estimates that are far below those provided by the FAO. They conclude that most previous studies of global land availability are far too optimistic about how much land is available for conversion to cropping activities without inflicting serious environmental damage.

The Lambin et al. (2013) study has important implications for future analyses of the indirect land use impacts of biofuels. First of all, it highlights the fact that there are important local constraints to land expansion in many regions which are not factored into most, if not all, global analyses of land cover change. In the case of the biophysical and socio-economic constraints, this suggests that the elasticity of land supply in some regions may be overstated—resulting in greater land scarcity than might otherwise be predicted in the wake of biofuels expansion. In addition, the authors highlight local environmental factors which extend well beyond carbon stocks, and include endangered species, unique ecosystems and the role of forests in regulating the water cycle. While private landowners seeking to expand their cropland will typically not factor these aspects into their decision making, the environmental costs of expansion into such locally sensitive areas will surely be greater than are captured by the economic models discussed in this review, which focus largely on carbon releases.

2.2. *Intensive margin of supply response*

The potential for producers to increase yields in response to higher prices is a critical factor in determining the pattern of land use change in response to biofuels-induced price rises. The larger this response, relative to the extensive margin, the smaller will be the required increase in area (Hertel 2011). The size of the yield elasticity to price has been a topic of intense debate, with some suggesting that CGE models have overstated this effect (Berry and Schlenker, 2011). Ultimately this is an empirical question, subject to statistical investigation.

Keeney and Hertel (2008) review the econometric yield elasticity estimates for corn in the US in the post WWII period and find that the estimates of the elasticity of corn yields with respect to corn price have been declining as the industry has consolidated and become more homogeneous. They choose a yield elasticity of 0.25 for use in their CGE model. Berry and Schlenker (2011) examine year to year variation in US corn yields and argue that the elasticity with respect to price is nearly zero, proposing 0.10 as their preferred value for the yield elasticity with respect to price. Huang and Khanna (2010) conduct a more extensive econometric investigation across several US crops and obtain an intermediate value for corn (0.15), with a higher yield response to price for wheat (0.43) and lower for soybeans (0.06). Goodwin et al. (2012) allow for intra-seasonal price response and obtain an estimate of 0.25. In short, it appears that the appropriate value for US corn lies likely somewhere between 0.10 and 0.25.

Unfortunately, the evidence for other commodities — and especially for other countries — is sparse. And yet, as Golub and Hertel (2012) document, the uncertainty in yield response to price in other major producing regions around the world is *far more*

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important for uncertainty in global land use change in response to US ethanol production than is the uncertainty in the US corn yield elasticity. This is a simple matter of arithmetic: since the rest of the world encompasses a much larger area, the yield elasticity in this region is more important in the global outcome. There is considerable evidence that the potential for supply response at the intensive margin is much greater in developing countries than in the US and Europe. For example, Potter et al. (2010) report nitrogen fertilizer application rates of less than 2.5 kg/ha on more than 50% of global cropland. Accordingly to their estimates, just 8.5% of the grid cells showing fertilizer applications account for more than 50% of global nitrogen fertilizers applied. Clearly raising application rates from this low level on the other 90+% of global croplands is likely to have a significant impact, and higher world prices for crops will provide the incentive to do so.

More generally, high commodity prices may be expected to provide other incentives to invest in boosting agricultural productivity—both on farms and in research stations. Indeed, Fulginiti and Perrin (1993) find evidence for a large and statistically significant influence of output prices on agricultural productivity in a set of developing countries. Specifically, they find that a 10% rise in past agricultural prices boosts current agricultural productivity by 1.3%.

While the intensification of production around the world will moderate the need for cropland expansion at the extensive margin, increased fertilizer use, in particular, carries with it significant potential for environmental impacts (Ramankutty, 2010; Tilman et al., 2002; Foley et al., 2005). Nitrogen fertilizer applications are a major source of GHG emissions, accounting for a significant share of total GHG emissions from agriculture as a whole (Baumert et al., 2009). In addition, agricultural runoff, coupled with excess nitrogen applications has resulted in the eutrophication of waterways (Vitousek et al. 2009). This kind of tradeoff is at the heart of the ongoing 'land-sparing vs. land-caring' debate in the ecology and environmental biology literature (Balmford et al., 2005).

2.3. Demand response to price

As noted above, if demand is relatively responsive to price, then this can moderate the need for supply expansion. Of course diminished consumption of food may not be a desirable outcome—particularly in parts of the world where malnourishment is most pervasive. FAO estimates that nearly 20% of the population in Sub-Saharan Africa and South Asia is malnourished (about 385 million people), with an average nutrition gap of nearly 240 kcal/day (Food and Agricultural Organization (FAO)). Regrettably, it is precisely these low income households that are most responsive to price increases (Muhammad et al., 2011). Upon reflection, this is hardly surprising. A household spending 70% of its income on food and facing a 50% price rise represents will experience a 35% decline in real income unless it can reduce food consumption. Indeed, for low income households, with little savings and few assets, it is impossible to accommodate such a development without reducing food consumption. On the other hand, for a high income household (e.g., in the US) which might spend just 10% of its income on food, a 50% price rise can be fairly readily accommodated by adjusting its consumption of non-food items this is just a 5% decrease in real income. An additional factor muting the impact on these high income households is the high level of post-farm value-added in the consumers' purchases. Therefore a 50% increase in commodity prices translates into a far smaller rise in consumer food costs in the wealthy economies.

In practice, the farm level elasticity of demand facing producers depends not only on the behavior of consumer demand for food, but also the demand for agricultural intermediate inputs into livestock production and food processing, and on the price-responsiveness of biofuels demand. In the case of livestock feed demand, there is notably significant potential for substitution amongst feedstuffs (Beckman et al., 2011). However, there is generally less substitutability among raw agricultural products in the case of food processing for human consumption. The biofuels demand component is very different from the other sources of derived demand in that that biofuels demand is often predetermined by government mandate. In the US, this mandate represents a fixed volume of biofuels each year, and in the EU and Brazil, it is a share of total consumption. In either case, the mandates make the demand for biofuel feedstuffs, at any given time period, very inelastic. For example, in 2012 in the US, the corn ethanol mandate was 13.2 billion gallons, regardless of corn price, so the drought that sent corn prices over $315/MT did not significantly affect corn use for ethanol.

Hertel et al. (2012) examine the aggregate demand response for all these combined sources of farm product demand and assess, at global scale, the relative importance of the demand margin, relative to the other margins of economic response. In their analysis of the global response to the International Energy Agency's projections of biofuel production growth over the 2006—2035 period, under current policies, those authors find that, with the extensive margin alone in place, global cropland would expand by a projected 8.7%. Bringing the intensive margin of supply response into play drops the global land requirement to 3.8%, and adding the demand margin only reduces it to 3.1%. So the bulk of the 'work' in mitigating the global scarcity induced by biofuels appears to come from the extensive and intensive margins of supply.

2.4. Spatial patterns of market responses to scarcity

As shown in Fig. 3, the global cropland response to increased demands for biofuels and foodstuffs is by no means uniform. And, as noted above in the case of irrigation constraints, any biofuels-induced shifts in this pattern of land use change can have important implications for the total increase in cropland area, as well as the ensuing GHG emissions. So the question arises: what determines this pattern of global land use change? First and foremost is the extent to which property rights are established and encroachment onto wild lands is not permitted. Another important determinant of global land use change is the degree to which governments are able to insulate domestic producers and consumers from world price changes. Martin and Anderson (2012) find evidence of significant market insulation during the recent food price spikes—particularly in the short run. Over the longer run, it is more difficult to remain insulated from world markets.

To date, the simulation models used to examine the iLUC effects of biofuels have adopted one of two competing hypotheses about the distribution of cropland change in the wake of biofuels growth. The first of these is the so-called 'Integrated World Markets' (IWM) hypothesis. In this case, there is effectively just a single global market for corn, and, absent border interventions, we expect to see a rather uniform expansion of cropland worldwide. Of course, the largest proportionate responses will be in those regions with large land supply elasticities, but overall, the IWM hypothesis argues that producers worldwide will respond to the biofuels shock. This hypothesis is evidenced in the early iLUC estimates of Searchinger et al (2008), who estimated that cropland in India and China would expand by more than 1 million hectares each, in response to a 15 billion gallon expansion of the US corn ethanol program.

The competing hypothesis is the 'Differentiated Products' (DP) hypothesis, which posits that corn is not a homogeneous product, but rather is differentiated by region of origin. Within this framework, there is an important role for the current geography of trade. The CGE models used for iLUC analysis all employ the DP hypothesis, leading to their finding that the largest iLUC impacts are felt by the trading partners and export competitors of the region initiating the biofuels program. This means, for example, that a US biofuels program will have less impact on land use in India, than would be expected under the IWM hypothesis. Given the regional differences in yields and carbon stocks, whether one adopts the IWF or DP hypothesis can greatly affect the iLUC estimates. If the DP stance is adopted, there is the issue of exactly how differentiated are the products in question. This is an area where empirical work is sorely needed to discriminate between these competing views of the world.

Villoria and Hertel (2011) develop an econometric model that permits them to compare the IWF and DP hypotheses in the context of demand or supply shocks in the US coarse grains market. Their model, estimated using annual FAO data over the period: 1975—2002, rejects the IWM hypothesis in favor of the DP model. Furthermore, they find that the preferred, DP model results in just half the iLUC emissions from a US biofuels program than that predicted using the IWM model, because those countries most closely integrated with the US coarse grains sector tend to have higher yields and lower emissions factors. Clearly understanding the spatial distribution of the market-mediated effects flowing from a biofuels program is very important.

3. Market-mediated effects due to cellulosic feedstocks

Early expectations signaled that cellulosic (or second generation) biofuels would have very positive GHG emissions benefits compared with fossil fuels, and would not compete with food markets. Taheripour and Tyner (2012) have now examined this issue in detail. Their results indicate that authors suggesting little or no land use impacts from dedicated energy crops could be misleading. The land use impacts of producing biofuels from dedicated crops is not zero because the opportunity costs of using cropland pasture is not zero. Livestock producers will not give up their cropland pasture without compensation. The fact is that there is little completely idled land, especially in the U.S. Indeed, there is a strong tendency of biofuels advocates to overstate the amount of available cropland, whereas more refined analyses of land use, land tenure and availability inevitably produce much smaller estimates (Lambin and Meyfroidt 2011).

In their study, Taheripour and Tyner (2012) find that crop residues do not cause iLUC because they are a co-product with corn production. However, dedicated energy crops such as miscanthus and switchgrass do compete directly with other land uses. The extent of iLUC-induced GHG emissions depends on the yield of the dedicated energy crop and the biofuel conversion efficiency. With the assumptions used in Taheripour and Tyner (2012), miscanthus achieves significant GHG emission savings, but switchgrass, with its lower yield, has GHG emissions that are not much different from corn ethanol. The authors also find that cellulosic conversion to drop-in fuels, such as bio-gasoline, is much more efficient that conversion to ethanol.

Ultimately the role for second generation biofuels in the global economy will depend heavily on future energy prices (Hertel, Steinbuks, and Baldos 2012). This is a different, but equally important type of market-mediated effect. In this case, higher energy prices encourage more biofuel production, while rendering intensification through the application of nitrogen fertilizers less attractive, due to their dependence on natural gas as a feedstock. These two forces combine to boost returns to cultivated land, thereby encouraging further expansion at the extensive margin in the face of higher energy prices.

Other technologies, such as biofuels from algae, are further down the horizon. At this point, too little is known about these technologies to produce any credible estimates. In fact, there remains considerable uncertainty regarding GHG emissions for any of the cellulosic pathways because there is no commercial scale production, and lots of remaining uncertainty about crop yields, conversion efficiency, and a host of other factors.

4. Other environmental impacts of biofuels

Use of fossil fuels for transportation entails significant negative environmental impacts. The research that has been reported to date generally attempts to compare the environmental impacts of biofuels with fossil fuels. The National Academy report on this topic (National Research Council, 2011) provides one of the most comprehensive assessments of environmental impacts of biofuels and the large uncertainties involved in getting accurate estimates. That report covers GHG emissions, air quality, water quality, water use, soil erosion, biodiversity, and ecosystem services changes associated with biofuels. In general, the analysis makes two important points. First, there is likely to be a significant difference in most of these areas between first and second generation biofuels. For example, corn ethanol barely meets the federal GHG reduction standard of 20% (U.S. Congress, 2007), but some of the second generation biofuels generally achieve much larger GHG reductions, thereby meeting the higher 50 percent standard. First generation biofuels may increase chemical and/or soil runoff from additional corn area, whereas second generation perennial crops use less fertilizer and do a better job of retaining soil.

The second major point is that many of the environmental impacts are site-specific and pathway dependent. For example, in one area, with given soil properties, slope, etc., removal of corn stover for production of second generation biofuels may not pose a problem, but in another area it could result in loss of soil organic matter and increase erosion. The outcome also depends on how the land is managed. For example, corn stover removal with a cover crop in place might not cause any adverse environmental problems, whereas, in the absence of a cover crop, significant problems could emerge. Each location and each conversion technology will differ, making it very difficult to generalize about these broader environmental impacts.

5. Conclusions

There are several key conclusions that emerge from this review. First, and perhaps foremost, there is now clear evidence that market mediated land use response to crop price changes is real. *Markets work!* Farmers around the world have responded to the higher crops prices over the past five years with substantial increases in area harvested field crops, and we expect that yield growth rates are also higher as a consequence of increased investments in the sector. Second, while the focus of this paper has been on land use change, the environmental impacts of biofuels are far-reaching and not limited to land use change. Some of the environmental impacts may be positive, such as increased wildlife habitat provided by perennial biomass crops, but others, such as increased chemical runoff and soil erosion are not.

Third, despite all the research that has been done and all the advances made, there is still considerable uncertainty in the estimates of biofuels induced land use change. Obtaining tightly bounded estimates of these impacts is likely beyond the reach of current models and data.

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