IOP Publishing Environmental Research Letters

Environ. Res. Lett. **2** (2007) 044004 (9pp) doi:10.1088/1748-9326/2/4/044004

Challenge of biofuel: filling the tank without emptying the stomach?

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Received 22 June 2007
Accepted for publication 14 November 2007

Abstract

Biofuels have become a leading alternative to fossil fuel because they can be produced domestically by many countries, require only minimal changes to retail distribution and end-use technologies, are a partial response to global climate change, and because they have the potential to spur rural development. Production of biofuel has increased most rapidly for corn ethanol, in part because of government subsidies; yet, corn ethanol offers at most a modest contribution to society's climate change goals and only a marginally positive net energy balance. Current biofuels pose long-run consequences for the provision of food and environmental amenities. In the short run, however, when gasoline supply and demand are inelastic, they serve as a buffer supply of energy, helping to reduce prices. Employing a conceptual model and with back-of-the-envelope estimates of wealth transfers resulting from biofuel production, we find that ethanol subsidies pay for themselves. Adoption of second-generation technologies may make biofuels more beneficial to society. The large-scale production of new types of crops dedicated to energy is likely to induce structural change in agriculture and change the sources, levels, and variability of farm incomes. The socio-economic impact of biofuel production will largely depend on how well the process of technology adoption by farmers and processors is understood and managed. The confluence of agricultural policy with environmental and energy policies is expected.

Keywords: biofuels, tax credit, welfare, adoption, agricultural biotechnology, climate change

1. Introduction

The emergence of biofuels in some ways marks a return to the past. During the 19th century, as much as 20% of agricultural land in the US was devoted to producing fodder for horses that pulled carriages. Today, liquid biofuels like ethanol and biodiesel comprise about 4% of US fuel consumption[4]. Overall, liquid biofuels comprise a mere 1.2% of global renewable energy supply, with the bulk of renewable energy supplied by traditional biomass and used for cooking and heating in Asia and Africa (IEA 2006). Liquid biofuels can today be classified into three main sources of production: sugarcane ethanol from Brazil, corn ethanol from the United States, and rapeseed biodiesel from Germany. Brazil and the United States together produce about 90% of the 36 billion litres of ethanol produced globally, while Germany accounts for over 50% of the 3.5 billion litres of global biodiesel production (Martinot 2005). In the rest of the paper we use the term biofuels to refer exclusively to liquid biofuels.

US ethanol production is supported by regulation-induced demand, a \$0.51 per gallon tax credit and a \$0.54 per gallon tariff on imported ethanol. Although both government support and high oil prices have been a catalyst for the recent ethanol

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[3] Member of Giannini Foundation.

[4] Approximately 6 billion gallons of ethanol and 140 billion gallons of gasoline in 2006 http://eia.doe.gov

Table 1. Global potential for ethanol from principal grain and sugar crops.

Crop	Global acreage (million hectares)[a]	Global average yield (tons/hectare)[a]	Global production (million tonnes)	Conversion efficiency (litres/tonne)[b]	Land intensity (litres/hectare)	Maximum ethanol (billion litres)	Gasoline equivalent (billion litres)	Supply as % of 2003 global gasoline use[c] (%)
Wheat	215	2.8	602	340	952	205	137	12
Rice	150	4.2	630	430	1806	271	182	16
Corn	145	4.9	711	400	1960	284	190	17
Sorghum	45	1.3	59	380	494	22	15	1
Sugarcane	20	65	1300	70	4550	91	61	6
Cassava	19	12	219	180	2070	39	26	2
Sugarbeet	5.4	46	248	110	5060	27	18	2
Total	599					940	630	57

[a] Data from FAO online statistical database.

[b] Data from various sources.

[c] Global gasoline use in 2003 = 1100 billion litres (Kim and Dale 2004).

boom, liquid biofuels have several advantages over other alternative energy technologies. First, because their physical and chemical properties allow easy blending with gasoline or diesel, biofuels require relatively minor adjustments to existing engine technology and fueling infrastructure. As a result, adoption of biofuels by end-users will occur more quickly. Second, most countries can produce biofuel domestically, lessening demand for oil imports. Biofuels, therefore, address several political economy considerations, including support for rural economies and national security. They are not, however, without costs. They will impose pressure on food and water supplies as well as the environment. For these reasons, biofuels now garner protest from some environmentalists who had championed them as a solution to global warming.

This paper estimates the maximum amount of ethanol that could be produced from principal food crops today if they were diverted entirely to energy production. We then outline a conceptual framework for analyzing the impact of biofuel production on food and fuel prices. We employ this framework to develop back-of-the-envelope estimates of wealth transfers resulting from biofuel production. We then discuss the implications for agriculture of the second generation of biofuels. Finally we conclude with some insights for policy.

2. Resource footprint of biofuels today

An extensive literature compares the net intensity of energy consumption (and pollution generation) per unit of useful energy produced by biofuel and fossil fuels (Cleveland 2005, de Oliveira *et al* 2005, Farrell *et al* 2006, Pimentel and Patzek 2005, Sheehan *et al* 2003, Tilman *et al* 2006). One measure of energy intensity is the energy return on investment (EROI), which is defined as the ratio of useful energy delivered by an energy source to energy expended in obtaining that energy source. In the case of fuel such as gasoline or ethanol, it measures the amount of energy contained in a litre of fuel compared to the amount of energy expended in producing a litre of fuel. Cleveland (2005) reports an EROI of 9:1 for oil whereas Farrell *et al* (2006) report the EROI for US-produced corn ethanol in the range of 1.2–1.6. Hall *et al* (2003) argue that corn ethanol is not sustainable because of its low EROI. Moreover, the greenhouse gas emissions reductions of corn ethanol are reported to be marginal at best (Farrell *et al* 2006). Corn ethanol is, therefore, ineffectual from a climate change perspective and also unsustainable from an energy efficiency perspective. Sugarcane ethanol in Brazil is reported to offer higher energy return and greenhouse gas reductions per litre of ethanol than US-made corn ethanol (Goldemberg 2007). Like corn ethanol, however, sugarcane ethanol production is associated with externalities that must also be included in the calculus of biofuel sustainability.

Biofuel is a land and water intensive technology. Production of biofuels takes land away from its two other primary uses—food production and environmental preservation. As farming expands to produce energy crops, soil erosion may worsen, application of chemical pesticides and fertilizers may expand and biodiversity may suffer on shrinking environmental lands. A positive net energy balance, therefore, is not sufficient for sustainability. In fact, sugarcane ethanol can appear unsustainable based on the impact its production has on water alone (de Oliveira *et al* 2005). Likewise, palm biodiesel production in Indonesia is viewed as unsustainable because of its consequences for tropical rainforests (Curran *et al* 2004).

In table 2 we report theoretical estimates for global ethanol production from the principal grain and sugar crops based on global average yields and commonly reported conversion efficiencies. The seven crops listed in the table account for 42% of the global stock of cropland today[5]. Utilization of the entire supply of these seven crops for bioenergy production would account for about 57% of global gasoline consumption today[6]. A hypothetical, but more realistic, scenario in which 25% of each of the principal crops and residues is devoted

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[5] 599 million hectares out of 1400 million hectares of crop land worldwide (http://faostat.fao.org).

[6] Gasoline consumption in 2003 was approximately 1100 billion litres (Kim and Dale 2004).

Table 2. Back-of-the-envelope welfare estimates of US ethanol production.

Gasoline market		
Global gasoline consumption in 2006		600 billion gallons
US gasoline consumption in 2006		140 billion gallons
Global ethanol production in 2006[a]		13 billion gallons
US ethanol production in 2006[a]		4.9 billion gallons
Price elasticity of gasoline demand		−0.23
Price elasticity of gasoline supply		0.25
% increase in fuel supply due to ethanol (adjusted for energy equivalence)		1.5%
% decrease in fuel price due to ethanol		3%
Average retail gasoline price for 2006	$	2.53 per gallon
Price of gasoline in the absence of ethanol supply	$	2.61 per gallon
Increase in surplus to US gasoline consumers	$	11.0 billion
Increase in surplus to ROW[b] gasoline consumers	$	36.3 billion
Corn market		
Total US corn production in 2006		12.5 billion bushels
Efficiency of conversion of corn to ethanol		2.7 gallons per bushel
Amount of corn allocated to ethanol in US		1.8 billion bushels
% of corn used for ethanol in US		15%
% of corn production exported by the US		17%
Price elasticity of corn demand		−0.5
Price elasticity of corn supply		0.2
% increase in corn price due to ethanol		21%
Average price of corn for marketing year 2006–2007	$	3.00 per bushel
Price of corn in the absence of ethanol demand	$	2.48 per bushel
Increase in surplus to US corn producers	$	6.4 billion
Loss in surplus to US corn consumers (domestic non-ethanol corn users)	$	4.4 billion
Loss in surplus to ROW corn consumers	$	1.1 billion
Tax cost		
Volumetric excise tax credit in US	$	0.51 per gallon
US taxpayer cost of tax credit	$	2.5 billion

[a] http://www.ethanolrfa.org/industry/statistics/#F.

[b] ROW—rest of the world.

to ethanol production yields a 14% offset in gasoline use. Similar calculations based on cropping patterns, yields and conversion technologies suggest the United States, Canada and EU-15 would require between 30% and 70% of their respective current crop area if they are to replace 10% of their transport fuel consumption with biofuels (OECD 2006). According to Goldemberg (2007), about 33 million hectares of sugarcane crop land worldwide can displace about 10% of the global gasoline demand. This compares well with our estimates shown in table 2.[7] It is likely far more cropland will be needed to offset these shares of gasoline consumption in the future as the demand for energy grows, particularly in the transportation sector.

While these figures suggest that current biofuel technologies cannot replace fossil fuels, they should not overshadow the fact that biofuels provide benefits even if they account for only a small share of energy consumption. In particular, the effect of biofuels on energy prices has been neglected in the literature. A simple welfare analysis can, however, determine the orders of magnitude of these benefits, and we turn our attention to that analysis next.

3. Back-of-the-envelope welfare estimates of US ethanol tax credit program

A stylized model of supply and demand for a crop that has multiple uses, like food and fuel, is shown in figure 1. We assume that the demand for biofuel is initially low (figure 1(a)) due, perhaps, to low oil prices or the absence of environmental regulation. Therefore, no biofuel is produced in the initial equilibrium (price P_0 and quantity Q_0) determined by the intersection of total demand (d_{T0}) and supply (S_0). Amid rising demand for oil or in the presence of renewable fuel standards or other climate policies, the demand for biofuel increases, reflected by an upward shift in biofuel demand (figure 1(b)). For simplicity, we assume no change in commodity supply in the short run, so the short-run equilibrium is determined by the intersection of the new demand, d_{TS}, and supply, S_0. This new equilibrium is characterized by price P_S and quantity Q_S. Crop prices increase and food supply decreases ($Q_S^F < Q_0$). Total agricultural production may increase ($Q_S > Q_0$). In the long run (figure 1(c)), supply may increase, yielding the equilibrium denoted by P_L and Q_L. In this equilibrium, the price is lower than the short-run price, and both fuel and food supply are higher than in the short run. Productivity-enhancing technologies like agricultural biotechnology can

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[7] According to our estimates 20 million hectares of sugarcane grown world wide today can supply 6% of the global gasoline demand. This implies that 33 million hectares can meet 10% of gasoline demand.

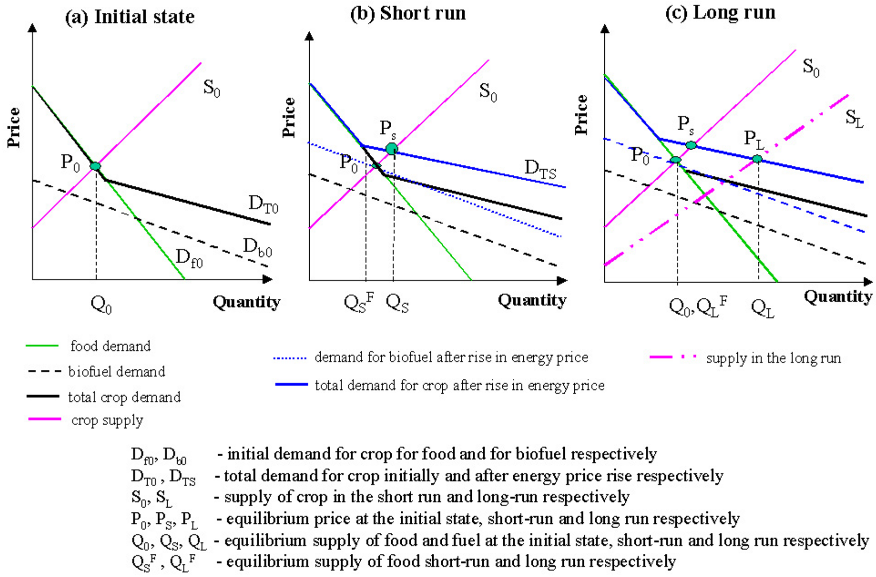

Figure 1. Conceptual model of supply and demand for corn.

increase supply without increasing the agricultural land base. A similar stylized model of short-run supply and demand for fuel is shown in figure 2. This figure also shows how the elasticity of supply and demand in the short run can determine the extent of impact of a new alternative supply on prices. The algebraic model is explained in the appendix.

We use this conceptual model to develop estimates of the costs and benefits of a \$0.51 ethanol production tax credit in the US in the year 2006. We parameterize our model of the corn market using a value of[8] -0.5 for the short-run price elasticity of demand for corn and 0.2 for the short-run price elasticity of corn supply. For the gasoline market, we assume the short-run price elasticity of demand and short-run gasoline price elasticity of supply as[9] -0.23 and 0.25, respectively. Given these assumptions, table 2 reports the wealth transfers from taxpayers and consumers of corn to producers of corn and consumers of gasoline (detailed derivation of the calculation of change in price of corn and gasoline as a result of ethanol supply are shown in the appendix). We estimate that high corn prices from ethanol demand benefited corn producers by \$6.4 billion USD while US gasoline consumers benefited by \$11 billion USD from cheaper gasoline. Since oil and by extension gasoline is a global commodity, US ethanol production also benefited gasoline consumers outside of the US to the tune of \$36 billion USD[10]. Thus even though gasoline prices in 2006 were higher than those in 2005, the supply of ethanol tempered the gasoline price increase for domestic consumers. The US ethanol program subsidizes gasoline consumers the world over. On the other hand US corn consumers suffered a loss of \$4.4 billion USD from the increase in corn price while the tax cost of ethanol production was \$2.5 billion USD[11]. Since about 17% of US corn production is exported and since the US is a large exporter of corn, high corn prices also hurt importers of corn. From the US perspective, the total benefits to gasoline consumers and corn producers was \$17.4 billion USD (\$11B USD+\$6.4B USD) while the total cost to consumers to corn and taxpayers was \$7.1 billion USD (\$4.5B+\$2.6B). It is obvious that we have not considered the loss to oil producers, some of whom are US companies. If the loss to US oil producers was less than \$10.3B then we can conclude that the US gained overall. From the perspective of the US consumer, there was a net surplus increase of \$4.4 billion USD (\$11B − \$4.4B − \$2.5B USD). Ethanol production also improves the terms of trade in both the export of corn and the import of oil, which we have not considered. Globally, we can unambiguously conclude that gasoline consumers and food producers gain, while food consumers and oil producers lose. Our estimates are of course sensitive to the short-run price elasticity of supply and demand used in the model. Higher elasticities for gasoline will obviously lower the impact on prices and hence the benefits of ethanol. We believe that these estimates are reasonable given that refineries appeared to be operating at close to full capacity in 2006[12].

Our intention in presenting these figures is not to arrive at any sort of normative policy conclusions, because our model

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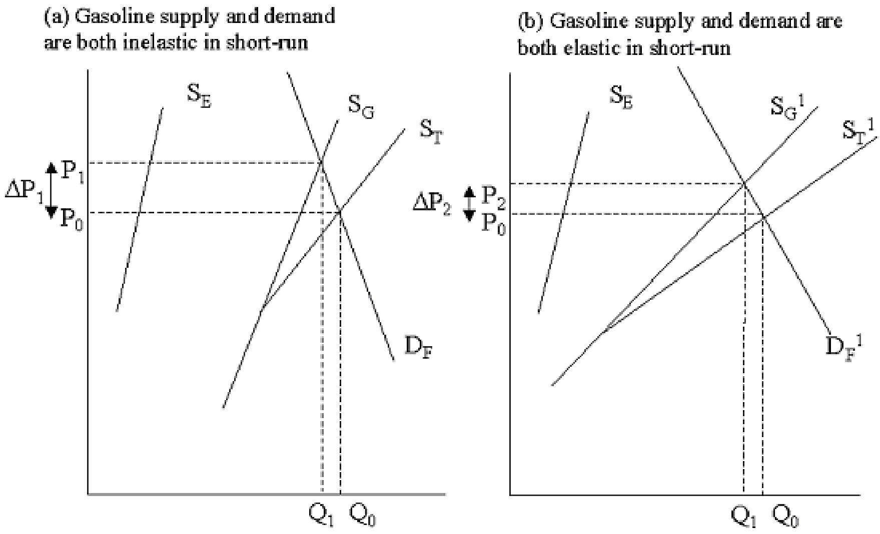
[8] Typical values suggested in *Economics of Agricultural Policies* by Bruce Gardner, Macmillan Publishing Company 1988.

[9] http://www.ftc.gov/reports/gasprices05/050705gaspricesrpt.pdf.

[10] We compute this under the assumption that the world average gasoline price is equal to the US average gasoline price. Obviously the reality is more complex because, although there exists a world oil market, there is no global gasoline price given the various levels of taxation it is subject to in the different countries.

[11] According a recent report prepared for the Global Subsidies Initiative suggests that the total direct and indirect support for ethanol in the US ranges between a low estimate of \$5.1 USD and a high estimate of \$6.7 USD. Using a value in this range for the total taxpayer cost will no doubt reduce the net benefits from the US perspective. Ignoring the loss to oil producers, even the high estimate for total taxpayer cost of subsidies to ethanol results in a net gain to the US consumers and corn producers.

[12] Installed oil refining capacity worldwide in 2006 was 85.34 million barrels per day (mbpd). The global average demand for oil in 2006 was 84.46 mbpd.



For the same ΔQ, $\Delta P_1 > \Delta P_2$, which implies that when supply or demand or both are inelastic, ethanol has higher impact on price of fuel and hence provides higher consumer surplus (ethanol demand is assumed inelastic in both cases)

Figure 2. Conceptual model of supply and demand for fuel.

makes several simplifying assumptions. One simplification has been that we have not considered other distortions such as import tariffs[13], renewable fuel mandates and deficiency payments. We have also not considered the impact on consumers resulting from scarcity-induced price increases in displaced commodities (soybeans and other crops) or the impact on the livestock industry and oil producers. Nor have we included the administrative costs of running government programs. We have not estimated the consumer surplus resulting from changes in emissions of carbon and other pollutants due to ethanol or the welfare effects of tariffs on ethanol imports. We have also assumed perfectly competitive markets for oil and gasoline. We, therefore, refrain from any calculation of net social impact and we emphasize that this analysis is instructive in terms of the orders of magnitude of transfers related to ethanol production. Our assumptions of elasticities are valid only in the short run when supply and demand are inelastic, whereas in the long run both supply and demand are elastic.

Despite these simplifications, the basic lesson that emerges is that support for ethanol benefits gasoline consumers and corn producers and harms food consumers and oil producers. This has significant distributional impacts. Food is a necessity whereas gasoline is a luxury good in much of the world. Higher food prices will particularly harm the poor, who spend larger shares of their budgets on food. Higher energy prices will benefit the wealthy, for whom food is a smaller part of the budget and energy is larger. It may be the case, therefore, that the poor go hungry so the wealthy can drive bigger cars farther. Technology changes these conclusions, and in the final two sections of this paper, we consider the role of technology in improving the welfare effects of a biofuel future.

4. Second-generation biofuels and the transition of agriculture

Whereas the first generation of biofuels has provided minimal contributions (if any) to carbon emission mitigation and has increased food prices and threatened natural habitat by bringing it into production of energy crop, the second generation of biofuels is expected to provide benefits beyond short-term gasoline price dampening, terms of trade improvements, and wealth transfers. The use of cellulosic biomass for energy production is expected to result in significantly higher EROI and carbon sequestration compared to starch and sugar based biofuel (Tilman *et al* 2006, Sheehan *et al* 2003, Farrell *et al* 2006)[14]. Just as corn is considered an unsustainable feedstock, ethanol is also not an ideal biofuel because of its hydrophilic nature, which increases the energy cost of distillation and renders it corrosive to the pipes that constitute gasoline distribution networks (Somerville 2007). Future biofuels may encompass a broader set of fuels such as bio-butanol or higher chain hydrocarbon fuels similar in composition to gasoline or diesel (Somerville 2007). According to the Intergovernmental Panel on Climate Change's (IPCC) fourth assessment report on climate change, second-generation biofuels are considered one of the key mitigation technologies for the transportation sector. They are expected to be commercialized by 2030 (IPCC 2007).

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[13] Along with domestic production subsidies, import tariffs have been effective in reducing the level of imports from Brazil. Imports from Brazil comprised 8% of US consumption. http://www.ethanolrfa.org/industry/statistics/#F.

[14] The net carbon offsets that these authors report do not consider the effect of direct or indirect deforestation that may result due to agricultural expansion. They either assume that cellulosic crops are grown on existing farm land or result in restoration of barren or unproductive marginal land with perennial crops.

Regardless of the ultimate form of biofuel, second-generation biofuels are likely to depend on cellulosic matter for feedstock, primarily because of the significantly higher yield per hectare of cellulose compared to sugar or starch crops[15]. Cellulosic conversion technologies will also enable the use of crop residues in biofuel production. In table 3 we report cellulosic energy production for a hypothetical scenario in which 100 million hectares of cropland are allocated to each switchgrass and miscanthus to produce lingo-cellulosic biomass. The table also shows the energy potential of crop residues. Under these assumptions, about 14% of today's global cropland along with crop residues from other agricultural lands could offset 91% of current global demand for gasoline.

How likely is it that about 200 million hectares of existing arable land can become available for growing non-food crops? An analysis by Waggoner (1995) of the demand for cropland suggests that by 2050, a world population of 10 billion could be supplied a daily diet of 3000 calories while using 200 million hectares less cropland than today. This would require productivity-enhancing innovations in agriculture. A study by the US Department of Energy and US Department of Agriculture estimates that about 22 million hectares of idle cropland, marginal land and pasture dedicated to perennial crops can yield about 377 million dry tons of biomass for bioenergy purposes in the US (DoE 2005). There also exists an extensive literature that estimates the potential for producing bioenergy mainly from wood harvested from plantations of fast-growing trees like poplar, willow, and eucalyptus and crop residues without using land under crops. A review of 17 such studies by Berndes *et al* (2003) concludes that estimates for potential contribution of biomass in the year 2050 range from below 100 EJ/yr to over 400 EJ/yr (EJ = exajoule (10^{18} J)). In comparison to the current level of bioenergy of 45 EJ/yr, this represents a doubling to a tenfold increase[16]. While technical feasibility studies provide a useful frame of reference, they do not explicitly acknowledge the constraints on achieving large-scale biofuel production, such as the necessary economic and institutional conditions necessary for achieving high levels of production. Nor do they consider the implications of large-scale production for agriculture and the environment, which may constrain production.

Large-scale production of new types of crops dedicated to energy production will change the agricultural landscape and the sources, levels and variability of farm income. The adoption of biofuel technologies likely requires policy intervention to coordinate adoption decisions by farmers and biorefineries. Traditionally, adoption decisions by farmers are analyzed within the context of markets with limited institutional setup. A manufacturer or dealer introduces either an improved variety of seed for an existing crop or introduces a new productivity-enhancing innovation (such as chemical fertilizers, pesticides, irrigation technologies, etc), extension specialists demonstrate to farmers how to use the innovation, and then farmers make a discrete choice to adopt or not adopt.

With biofuels and related technologies, the adoption process is more complex. The farmer is faced with a decision to grow a new crop for a new type of market, which did not exist before. His decision to switch to a crop like switchgrass or miscanthus will depend on whether or not he has a contract from a processor to produce the crop and whether or not the payoffs for producing the new crop exceed the payoffs from all alternate uses of the land. A processor will invest in a biofuel conversion facility provided he has an assured contract from the oil industry to produce biofuel. This requires demand for biofuel. Finally, a consumer's decision to purchase a flex-fuel vehicle depends on his expectation of his net benefits from investing in a flex-fuel vehicle. The adoption of biofuel, therefore, must be coordinated at four different levels of the economy: farmer, processor, oil industry and consumer.

Each of these stages in the adoption process involves risk. Policy is needed to reduce this risk. Policy may induce demand among consumers, regulate energy companies, induce investment by among processors and offer price assurances to farmers. The degree to which optimal policy involves intervention along each step in the supply chain is a topic for further research. In the US, renewable fuel standards renewed in the Energy Policy Act of 2005 ensure demand by requiring gasoline producers use 7.5 billion gallons of ethanol by 2012. The production tax credit incentivizes processors to invest in biorefineries, which guarantees farmers contracts. Consumers are offered incentives to adopt technologies compatible with reduced car emissions. The US government, therefore, has intervened at nearly every step in the supply chain to encourage adoption of biofuel technology. This may not be optimal. It may be sufficient to have intervention at any one step in the supply chain.

If coordinated adoption of biofuel occurs, then agriculture as we know it will be transformed. We will expect to see vertical integration in agriculture as firms seek to minimize risk. We may also see horizontal integration as firms attempt to capture benefits from coordinating production of related commodities. For instance, farmer cooperatives are investing in biorefineries. Corn processors and feed companies are investing in biofuel plants. The opportunities for risk-reducing and cost-saving integration can be expected to consolidate agriculture and give rise to more and bigger agribusiness. Furthermore, as food and energy production and environmental preservation become linked by biofuel, agricultural, energy and environmental policy will need to be integrated.

5. Biofuels in perspective

Biofuels can play an important role in our energy future, but there are several basic lessons to be learned from the

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[15] Non-cellulosic sources like sugar from sweet sorghum and oil from the seeds of the perennial shrub *Jaropha curcas* which can be used to produce ethanol and biodiesel respectively hold promise as future biofuel crops especially for cultivation on drought prone and marginal lands in tropical countries (Reddy *et al* 2005, Somerville 2007). However, the potential for achieving economic yield when grown with little or no inputs on marginal lands is uncertain today (Rajagopal 2007). Identification and breeding of high yielding varieties of drought tolerant biofuel crops should be one of the priorities of future research and development so that drought prone areas can also benefit from biofuel production.

[16] Since our focus here is on liquid transportation fuels we have not summarized this literature which we have reviewed in more detail in Rajagopal and Zilberman (2007). But we do recognize that when cellulosic technology is developed the conversion of wood to liquid biofuels may also become viable and so one could use the estimates of biomass production cited in those studies to determine the potential yield of transportation energy.

Table 3. Potential ethanol yield from switchgrass and miscanthus.

Crop	Global acreage in million hectares[a] (hypothetical scenario)	Average yield (tons/hectare)[b]	Global production (million tonnes)	Conversion efficiency (litres/tonne)[c]	Land intensity (litres/hectare)	Maximum ethanol (billion litres)	Gasoline equivalent (billion litres)	Supply as % of 2003 global gasoline use[d]
Switchgrass	100	10	1000	330	3300	330	220	20%
Miscanthus	100	22	2200	330	7260	726	490	44%
Crop residues			1500	290		442	296	27%
Total	200					1498	1006	91%

[a] A hypothetical scenario in which about 100 million hectares each are under switchgrass and miscanthus.

[b] Yield reported in Heaton *et al* (2004).

[c] Predicted conversion efficiencies reported in Khanna *et al* (2007).

[d] Global gasoline use in 2003 = 1100 billion litres (Kim and Dale 2004).

accumulated experience to date. First, unlike other alternative energy technologies, the impact of biofuels will be greater on food prices than energy prices. This is evident from the percentage change in prices for corn and gasoline shown in table 1. The effect of rising grain prices will be felt most acutely in developing countries, where grain comprises a larger share of the food budget. Simulation of scenarios involving successful commercialization of cellulosic technologies reveal that there is still likely to be a negative impact on food price, hunger and malnutrition especially in developing countries (Msangi 2007). Without adequate safeguards, further expansion of biofuels will mean an unpalatable trade-off between cars for the rich and starvation for the poor. We have suggested that rural and developing economies may benefit from greater demand for agricultural products, but those profits may be captured by land owners in the form of rents (Taheripour and Tyner 2007). In addition, the use of marginal lands for biofuel plantations may mean greater insecurity for the landless poor in developing countries who presently depend on low quality lands for their fuel wood and fodder needs (Rajagopal 2007).

Second, the need to increase agricultural production without expanding the land base makes improvements in agricultural productivity critical to our energy future. In the past half-century, agricultural productivity doubled because of innovations in inputs like irrigation and chemical fertilizers and pesticides. It may double in the next half-century, but productivity gains will need to be driven by other innovations. Agricultural biotechnology has already been demonstrated to increase yields and reduce inputs of harmful chemicals. Agricultural biotechnology may allow us to target improvements in the photosynthetic efficiency and content of cellulose, hemi cellulose and lignin. It may be possible to engineer plants to allocate greater quantities of carbon to stem growth as opposed to height growth, enhancing biomass production (Ragauskas *et al* 2006). While biotechnology has risks, the goal of environmental policy should be to compare relative risk of alternatives not the absolute risk of a given technology. This requires a new environmental paradigm that encourages small but measured risks in the near term in order to avoid large ones in the future.

Third, farmer adoption of specialized crops like perennial grasses will depend on whether they have a contract or a market for their product. This, in turn, depends on decisions to invest in processing capacity. The adoption of biofuels, therefore, is a two-step dance: industry must take the lead, and farmers will follow. But investments in processing capacity require long-term commitments to biofuels which may demand government incentives. While subsidies are necessary to minimize risk for investors, they are currently rigid and not linked to oil price, the impact on energy security, or environmental impacts (Koplow 2006). Incentives in the future should be dynamic and flexible so as to adapt to changing economic, political and environmental conditions. Agricultural and energy policy must be integrated. In particular, whereas agricultural policy has traditionally aimed to restrict supply to reduce downward pressure on commodity prices, an era of biofuels demands increased supply of certain crops. Policy, therefore, will need to change to enhance supply. Biofuels can serve to reduce the taxpayer burden by eliminating deficiency payments to farmers.

Finally, according to Smil (2000), 'long-term historical perspectives are truly invaluable; energy transitions are protracted, generations-long affairs; dubious claims made on behalf of small-scale, experimental and demonstration-size techniques are no substitutes for mercilessly critical appraisals based on the first principles; biased promotions of grand theoretical solutions rarely survive brutal encounters with scaling up for large-scale, reliable operations in the real world.' Biofuels should be one among a portfolio of policies that includes regulation of pollution through taxation or trading; energy efficiency and conservation; integrated planning of land use, zoning and transportation; and other technologies that are tried, tested and deployed to address the problems of climate change and rising energy demand. Taxation of pollution—a theoretically efficient policy—is made difficult because of political economy considerations. Nevertheless, pollution taxes should be part of our energy future.

6. Conclusion

Several researchers have analyzed the environmental and ecological implications of biofuels in detail. But there has been little economic assessment of the effects on various markets. In this paper, we have tried to delineate some of the short-run effects of expansion in US ethanol production on welfare. A simple welfare analysis of US corn ethanol suggests that the impact of producing biofuels from food crops will be greater on food prices than energy prices. We expect further expansion of current biofuels (and even future biofuels) to threaten food security. A smooth transition to a biofuel-intensive future requires considerable technical innovation, such as agricultural productivity growth, development and commercialization of cellulosic conversion, and a reduction in the resource intensity of biofuels.

Economics has a key role to play in ensuring a smooth transition to a biofuel future. Economists are responsible for designing incentives for technology adoption that are dynamic and ensure efficiency without having adverse effects on income distribution and the environment. The risks associated with cellulosic ethanol should not be discounted, but they should be measured relative to other energy alternatives.

Acknowledgments

This research was partially supported by a cooperative agreement with the US Department of Agriculture Economic Research Service (USDA-ERS).

Appendix A. Derivation of change in price of gasoline as a function of change in supply of ethanol

Let P be the equilibrium price; Q is the quantity at equilibrium; S^{E} is the ethanol supply function; S^{G} is the gasoline supply function; S^{T} is the total fuel supply; D^{F} is the total fuel demand; ε_D is the elasticity of demand for fuel; ε_S is the elasticity of supply for gasoline.

Now market clearing condition ⇒ Supply = Demand, i.e.,

$$S^{\mathrm{T}}(P) = D^{\mathrm{F}}(P)$$

$$S^{\mathrm{G}}(P) + S^{\mathrm{E}} = D^{\mathrm{F}}(P).$$

Differentiating each term, we get

$$S_p^{\mathrm{G}}\mathrm{d}P + \mathrm{d}S^{\mathrm{E}} = D_p^{\mathrm{F}}\mathrm{d}P$$

where

$$D_p^{\mathrm{F}} = \mathrm{d}D^{\mathrm{F}}/\mathrm{d}P, \qquad S_p^{\mathrm{G}} = \mathrm{d}S^{\mathrm{G}}/\mathrm{d}P,$$

$$\Rightarrow \frac{\mathrm{d}P}{\mathrm{d}S^{\mathrm{E}}} = \frac{1}{D_p^{\mathrm{F}} - S_p^{\mathrm{G}}} = \frac{1}{\varepsilon_D - \varepsilon_S}\frac{P}{Q}$$

where

$$\varepsilon_D = \frac{\mathrm{d}D^{\mathrm{F}}}{\mathrm{d}P}\frac{P}{Q} = D_p^{\mathrm{F}}\frac{P}{Q}$$

and

$$\varepsilon_S = \frac{\mathrm{d}S^{\mathrm{G}}}{\mathrm{d}P}\frac{P}{Q} = S_p^{\mathrm{G}}\frac{P}{Q}$$

$$\Rightarrow \mathrm{d}P = \frac{1}{\varepsilon_D - \varepsilon_S}\frac{\mathrm{d}S^{\mathrm{E}}}{Q}P.$$

If P^0, Q^0 is the initial price and quantity when ethanol is produced; P^1 is the price if there was no ethanol production; $\mathrm{d}S^{\mathrm{E}}$ is the decrease in ethanol production; $\mathrm{d}P$ is the change in price due to decrease in ethanol production;

$$\mathrm{d}P = \frac{1}{\varepsilon_D - \varepsilon_S}\frac{\mathrm{d}S^{\mathrm{E}}}{Q^0}P^0$$

$$P^1 = P + \mathrm{d}P,$$

⇒

$$\frac{\mathrm{d}P}{P^0} \propto \frac{1}{\varepsilon_D - \varepsilon_S}$$

implying that the higher the elasticity of supply or the elasticity of demand is, the lower is the percentage change in price.

Appendix B. Derivation of change in price of corn as a function of change in demand for ethanol

Similarly, in the corn market, let P be the equilibrium price; Q is the quantity at equilibrium; S^{C} is the corn supply function; D^{T} is the total corn demand fuel supply; D^{NE} is the total non-ethanol corn demand; D^{E} is the corn demand for ethanol; η_{D} is the elasticity of corn demand for non-ethanol; η_{S} is the elasticity of supply of corn.

Now market clearing condition ⇒ Supply = Demand, i.e.,

$$S^{\mathrm{C}}(P) = D^{\mathrm{T}}(P)$$

$$\Rightarrow S^{\mathrm{C}}(P) = D^{\mathrm{NE}}(P) + D^{\mathrm{E}}.$$

Differentiating each term, we get

$$S_p^{\mathrm{C}}\mathrm{d}P = D_p^{\mathrm{NE}}\mathrm{d}P + \mathrm{d}D^{\mathrm{NE}}$$

where

$$D_p^{\mathrm{NE}} = \mathrm{d}D^{\mathrm{NE}}/\mathrm{d}P, \qquad S_p^{\mathrm{C}} = \mathrm{d}S^{\mathrm{C}}/\mathrm{d}P,$$

$$\Rightarrow \frac{\mathrm{d}P}{\mathrm{d}D^{\mathrm{E}}} = \frac{1}{S_p^{\mathrm{C}} - D_p^{\mathrm{NE}}} = \frac{1}{\eta_s - \eta_D}\frac{P}{Q}$$

where

$$\eta_D = \frac{\mathrm{d}D^{\mathrm{NE}}}{\mathrm{d}P}\frac{P}{Q} = D_p^{\mathrm{NE}}\frac{P}{Q}$$

and

$$\eta_S = \frac{\mathrm{d}S^{\mathrm{C}}}{\mathrm{d}P}\frac{P}{Q} = S_p^{\mathrm{C}}\frac{P}{Q}$$

$$\Rightarrow \mathrm{d}P = \frac{1}{\eta_S - \eta_D}\frac{\mathrm{d}D^{\mathrm{E}}}{Q}P.$$

If P^0, Q^0 is the initial price and quantity when ethanol is produced; P^1 is the price if there was no ethanol production;

$\mathrm{d}D^{\mathrm{E}}$ is the decrease in ethanol production; $\mathrm{d}P$ is the change in price due to decrease in ethanol production;

$$\mathrm{d}P = \frac{1}{\eta_S - \eta_D}\frac{\mathrm{d}D^{\mathrm{E}}}{Q^0}P^0$$
$$P^1 = P + \mathrm{d}P,$$

$$\Rightarrow \qquad \frac{\mathrm{d}P}{P^0} \propto \frac{1}{\eta_S - \eta_D}$$

implying that the higher the elasticity of supply or the elasticity of demand is, the lower is the percentage change in price.

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