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The Energy Forum of the James A. Baker III Institute for Public Policy of Rice University

and

Rice University's Department of Civil and Environmental Engineering

Fundamentals of a Sustainable U.S. Biofuels Policy

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James A. Baker III Institute for Public Policy
Rice University

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James A. Baker III Institute for Public Policy and the
Rice University Department of Civil and Environmental Engineering

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About the Study: Fundamentals of a Sustainable U.S. Biofuels Policy

The Baker Institute Energy Forum and Rice University's Department of Civil and Environmental Engineering have embarked on a two-year project examining the efficacy and impact of current U.S. biofuels policy. Successful implementation of a sustainable biofuels program requires careful analysis of the potential strengths and weaknesses of the current mandated program. Corporate leaders are also in need of complete data to assess expanded industry participation in the biofuels area.

The United States is investing billions of dollars each year in subsidies and tax breaks to domestic ethanol producers in the hope that biofuels will become a major plank of an energy security and fuel diversification program. Moreover, the investment has grown in recent years.

This study assesses the value of the expensive program and its potential to meet the goal of enhancing energy security in an environmentally sustainable fashion. The policy research is designed to identify the steps necessary to avoid unintended negative impacts on sustainable development and the environment, including deleterious impacts on domestic agriculture, surface and ground water, and overall air quality in the United States. It also addresses the daunting logistical and economic challenges of expanding biofuels supplies into the U.S. fuel system and examines the costs and benefits of different options.

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About the Energy Forum at the James A. Baker III Institute for Public Policy

The Baker Institute Energy Forum is a multifaceted center that promotes original, forward-looking discussion and research on the energy-related challenges facing our society in the 21st century. The mission of the Energy Forum is to promote the development of informed and realistic public policy choices in the energy area by educating policymakers and the public about important trends—both regional and global—that shape the nature of global energy markets and influence the quantity and security of vital supplies needed to fuel world economic growth and prosperity.

The forum is one of several major foreign policy programs at the James A. Baker III Institute for Public Policy of Rice University. The mission of the Baker Institute is to help bridge the gap between the theory and practice of public policy by drawing together experts from academia, government, the media, business, and nongovernmental organizations. By involving both policymakers and scholars, the institute seeks to improve the debate on selected public policy issues and make a difference in the formulation, implementation, and evaluation of public policy.

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About the Rice University Department of Civil and Environmental Engineering

Rice University's Department of Civil and Environmental Engineering (CEE) was created in July 2001 when the Civil Engineering and the Environmental Science and Engineering departments merged. The goal of CEE is to build on the strengths of the two existing departments to create innovative programs in education and research designed to address questions of our society's growth and sustainability in a world of technological change. The department aims to prepare students to deal with major engineering challenges of the future and to assess the impacts of engineering decisions in global, ethical, and societal contexts. The program emphasizes environmental engineering, hydrology and water resources, structural engineering and mechanics, and urban infrastructure and management. Research projects involve collaborative efforts with professors and students from numerous departments and institutes across campus, resulting in an interdisciplinary research-based education that has benefited our graduate students intellectually and professionally.

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Medlock has served as an adviser to the Department of Energy in its energy modeling efforts and is a regular participant in Stanford University's Energy Modeling Forum. Medlock was the lead modeler of the Modeling Subgroup of the 2003 National Petroleum Council (NPC) study of North American natural gas markets, was a contributing author to the California Energy Commission's and Western Interstate Energy Board's "Western Natural Gas Assessment" in 2005, and contributed to the 2007 NPC study, "Facing the Hard Truths."

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I. Introduction

The United States is investing billions of dollars each year in subsidies and tax breaks to domestic ethanol producers in the hope that biofuels will become a major plank of an energy security and fuel diversification program. Moreover, this investment has grown in recent years. This study will assess the value of this expensive program and its potential to meet the goal of enhancing energy security in an environmentally sustainable fashion.

The Energy Policy Act of 2005 required 7.5 billion gallons of renewable fuel to be produced annually by 2012. More recently, Congress passed the Energy Independence and Security Act of 2007 on December 18, 2007, which increased the Renewable Fuel Standard (RFS) to require that nine billion gallons of renewable fuels be consumed annually by 2008 and progressively increase to 36 billion gallons by 2022. The bill specifies that 21 billion gallons of the 36 billion 2022 target must be "advanced biofuel," which on a life cycle analysis basis must encompass 50 percent less greenhouse gas (GHG) emissions than the gasoline or diesel fuel it will replace. "Advanced biofuels" include ethanol fuel made from cellulosic materials, hemicellulose, lignin, sugar, starch (excluding corn), and waste, as well as biomass-based biodiesel, biogas, and other fuels made from cellulosic biomass.

A smooth transition to a larger national biofuels program will require additional planning and policy analysis to avoid unintended consequences that might result from large-scale production and use of bioenergy in the United States. Greater knowledge is needed regarding the long-term environmental impacts of large-scale production and use, specifically as to whether the environmental attributes are indeed a net positive. Moreover, a better understanding is required of the logistical and economic challenges associated with extending biofuels beyond the current practice of blending corn-based ethanol as a 10 percent additive into the existing gasoline stock.

We endeavor in this report to provide an overview of some of the environmental, logistical, and economic challenges to a broader expansion of biofuels in the U.S. transportation fuel system, and we offer a broad range of policy recommendations to avoid some of the negative unintended consequences of implementing this ambitious goal. This report includes the following key findings:

Environmental and Health Impacts

- Ethanol is easily degraded in the environment and human exposure to ethanol itself presents minimal adverse health impacts;
- However, the addition of ethanol to gasoline will impede the natural attenuation of BTEX (benzene, toluene, ethylbenzene, and xylenes) in groundwater and soil, posing a great risk for human exposure to these toxic constituents present in underground storage tank leaks;
- Without major reforms in the regulation of farming practices, increases in corn-based ethanol production in the U.S. Midwest could cause an increase in detrimental environmental impacts, including exacerbating damage to ecosystems and fisheries along the Mississippi River and in the Gulf of Mexico and creating water shortages in some areas experiencing significant increases in fuel crop irrigation;
- Any clearing of forests and grasslands to grow biofuels will add to the release of carbon dioxide (CO_2) into the atmosphere;
- The production and use of E-85[1] ethanol fuel is not carbon neutral. Rather, it is uncertain whether existing biofuels production provides any beneficial improvement over traditional gasoline, after taking into account land use changes and emissions of nitrous oxide. Legislation giving biofuels preferences on the basis of greenhouse gas benefits should be avoided.

Logistics

- It will be difficult and expensive to reach congressionally mandated levels for renewable fuels if corn-based ethanol is the main product for achieving such targets. Based on the latest available U.S. Government Accountability Office data, which is for the year 2008, the U.S. government spent $4 billion in subsidies to replace about 2 percent of the U.S. gasoline supply. The average cost to taxpayers for these "substituted" traditional gasoline barrels was roughly $82 per barrel, or $1.95 per gallon (gal) on top of the gasoline retail price.

[1] E-85 is shorthand for 85 percent ethanol and 15 percent gasoline fuel blends.

- Limitations in the economies of scale in ethanol production pose a significant barrier to overcoming the logistical issues that block the widespread distribution of ethanol around the United States. While U.S. gasoline is distributed mainly by pipeline, the current U.S. ethanol distribution system is dependent on rail, barge, and truck transportation, which is much more costly than pipeline. With current technology, it is unlikely that an effective pipeline distribution system can be developed for ethanol transport. Instead, major refining companies in the United States are working to develop second generation non-ethanol biofuels, such as algae-based fuels, that can be transported more easily by pipeline;
- At present, the ethanol distribution system is plagued by bottlenecks that will be difficult to eliminate, making it virtually impossible for some states to achieve a 10 percent average content of ethanol in gasoline, unless existing barriers to trade from the Caribbean and South America are removed. The potential for production of ethanol in Latin America and the Caribbean is high, and much of it could be delivered to U.S. coastal regions at a lower cost than shipping corn-based ethanol from the U.S. Midwest. This could substantially help the Gulf Coast states successfully meet a 10 percent ethanol content;
- Introduction of E-85 fuel to increase the average use of ethanol in the U.S. fuel system beyond 10 percent ethanol faces major logistical problems. At present, no automobile manufacturer will extend an engine or parts warranty for vehicles that use more than 10 percent of ethanol content in fuel, except for vehicles specifically designed to run on E-85 fuel. This means that the majority of cars on the road today in the United States are not under warranty for anything other than gasoline containing 10 percent ethanol or less. E-85 flex-fuel vehicles stood at only 3 percent of the car fleet as of March 2009 and the availability of E-85 refueling stations is mainly limited to only one region of the United States (Styles and Acosta 2009). The use of E-85 or flex-fuel vehicles is not likely to be extensive enough to counterweigh the number of markets that cannot achieve E-10 saturation.[2] For E-85 to expand in the manner implied by U.S. congressional legislation, consumers would have to be educated to purchase the appropriate vehicles and refueling stations must be appropriately equipped and sited.

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[2] E-10 is shorthand for 10 percent ethanol and 90 percent gasoline fuel blends.

II. U.S. Biofuels Policy

Interest in biofuels as an alternative transportation fuel has percolated for many years. Propelled by concerns related to energy security and climate change, the federal government has in recent years backed various initiatives to push ethanol as a U.S. transportation fuel to new heights.[3] The Energy Independence and Security Act of 2007 (EISA) set targets for renewable fuels of 9 billion gallons annually for 2008, expanding to 36 billion gallons per year by 2022.[4] Corn ethanol production, under the new bill, is to be capped at 15 billion gallons per year, or close to 1 million barrels a day (b/d), in 2015. The bill specifies that 16 billion gallons per year should come from cellulosic ethanol by 2022. Notably, the RFS implemented as part of the Energy Policy Act of 2005 (EPAct) had more modest targets, mandating 7.5 billion gallons of ethanol and biodiesel by 2012. So, the push to expand ethanol use has accelerated in recent years. To date, 2009 mandates for advanced biofuels, such as those made from cellulosic materials or other nonfood crops, do not appear to be achievable and will be rolled into 2010 mandates.

Despite the policy push for increased ethanol use, there is a debate about the efficacy of a U.S. biofuel policy among politicians, economists, environmentalists, and lobbyists. Debate has centered on issues such as:

- Whether corn-based ethanol should be emphasized in U.S. policy over other, possibly more efficient, sources of renewable fuels;
- Whether ethanol-blended fuels can be safely introduced into existing vehicle fleets;
- Whether the logistics and economics of transporting large quantities of ethanol are favorable to a sustainable program.

[3] One influential report to policymakers from Oak Ridge National Laboratory (ORNL), titled "Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply," was released in April 2005 and is commonly referred to as the "Billion-Ton" report. It concluded that U.S. forestry and agriculture land resources could sustainably provide for more than 30 percent of current petroleum consumption. Subsequently, in July 2006, the DOE issued, "Breaking the Biological Barriers to Cellulosic Ethanol: A Joint Research Agenda," asserting a goal to "make biofuels practical and cost-competitive by 2012 ($1.07/gal ethanol) and offering the potential to displace up to 30 percent of the nation's current gasoline use by 2030."

[4] "Renewable fuel" is defined as motor vehicle "fuel that is produced from renewable biomass and that is used to replace or reduce the quantity of fossil fuel present in a transportation fuel." Renewable fuel therefore includes conventional biofuel and advanced biofuels like cellulosic biofuel, waste-derived ethanol, and biodiesel. RFS2 includes the first definition of/requirement to use "renewable biomass." Further, it creates land use restrictions limiting renewable biomass to existing agricultural land prior to December 19, 2007, and excludes "new" land from being used in the production of feedstock for advanced renewable fuels [*Title II – Energy Security through Increased Production of Biofuels, SEC.201. Definitions.* Energy Independence and Security Act of 2007. H.R.6.].

- Whether the net energy balance of renewable fuels is positive (i.e., whether there is a net gain in supply once the use of energy in the conversion and transport of renewable fuels is taken into account) and, hence, actual energy security benefits are achieved by moving to greater use of ethanol; and
- Whether environmental security concerns are addressed with renewable fuels. Some research shows that the net carbon emissions from renewable fuels are often higher than traditional transportation fuel emissions.

These issues call into question the feasibility of legislated targets for ethanol use.

Nevertheless, recent history has bolstered the case for renewable fuels as a means of achieving greater energy security. Driving is part of the American way of life. The United States is the world's largest energy consumer, and increasing gasoline consumption is the single most important factor behind rising U.S. dependence on foreign oil. At present, gasoline has no major substitute fuel that can be quickly and broadly disseminated into widespread use across the United States during a major disruption or oil pricing shock.

Because many households may find it financially imprudent to change their mode of transportation (whether just the engine or via a new vehicle purchase), the ability of consumers to substitute away from a particular level of motor fuel consumption is limited in the immediate term. In other words, gasoline demand is highly price-inelastic in the short run. Thus, large or abrupt changes in motor fuel supply and prices can have a substantial impact on consumers' discretionary spending. It has therefore been proposed that renewable fuels, which can be used in the existing vehicle fleet, would be the best potential substitute for traditional gasoline. It has been argued that supplementing the existing gasoline supply pool with renewable fuels could help lessen U.S. dependence on foreign oil and reduce the impact of oil shortages on the U.S. economy.

Between the summers of 2003 and 2008, a fivefold increase in crude oil prices, culminating with a near 50 percent increase in price in the first half of 2008, pushed policymakers in oil importing nations to rethink national strategies regarding oil import dependence. For Americans, this dramatic price increase in international crude oil markets translated into a sudden rise in U.S. gasoline retail prices—from about $2.00/gal in early 2007 to more than $4.00/gal in the summer of 2008.

High and wildly fluctuating gasoline prices are a problem for average Americans and small transport-dependent businesses, and high fuel costs general present a hardship on low-income and middle-class households. In the summer of 2008, when gasoline prices peaked, Americans earning $10,000 per year were spending up to 15 percent of their household income on gasoline, double the percentage in 2001 (Davis and Weiss 2008). With little ability to switch fuels in the transportation sector, this pushed members of Congress to investigate means to keep prices in check. Among the issues debated in Washington was the effect of America's reliance on crude oil as an energy source.

America's heavy reliance on crude oil and petroleum products was also highlighted during the aftermath of Hurricanes Rita and Katrina in 2005 and again after Hurricane Ike in 2008. Due to severe damage to Gulf Coast refinery infrastructure, fuel was in short supply and Americans in many parts of the country sat in gasoline lines for the first time since the 1970s. These events prompted policymakers to reconsider measures that would reduce national dependence on oil as an energy source, imported or not.

Rising gasoline use is the driving factor behind America's heavy dependence on crude oil, and more than 60 percent of U.S. crude oil supply is imported. This, in turn, puts negative pressure on the U.S. trade balance and the strength of the U.S. dollar. The U.S. oil import bill totaled $327 billion in 2007—triple that in 2002—and accounted for more than 40 percent of the overall U.S. trade deficit, compared to only 25 percent in 2002. This rising financial burden has exerted inflationary pressures and created ongoing challenges for the U.S. economy. Sudden, massive financial transfers to oil producing countries have also created new challenges for U.S. national security and contributed to speculative bubbles in global financial markets. In his 2007 State of the Union address, President George W. Bush noted that that U.S. dependence on imported oil makes it "more vulnerable to hostile regimes, and to terrorists—who could cause huge disruptions of oil shipments, raise the price of oil, and do great harm to our economy" (Bush 2007).

To aid in reducing oil dependence, the president and U.S. lawmakers promoted the idea that biofuels could diversify the U.S. fuel system and reduce dependence on foreign oil. The concept was introduced that an intensive program to develop domestic biofuels, together with improvements in automobile fuel-efficiency, would allow the United States to reduce its gasoline use by up to 15 percent. It was hoped that biofuels could provide a ready substitute if the price of oil were to rise too sharply, shielding the economy from the negative impact of disruption of oil. Subsequently, Congress passed regulatory targets for the amount of biofuels to be added to the U.S. gasoline supply. Initial stages focused on corn-based ethanol from the U.S. Midwest. Eventually, the U.S. biofuels program is targeted to expand to include “advanced” biofuels from cellulosic waste, but a commercially viable process for the wide-scale production of cellulosic biofuels has yet to be launched.

U.S. ethanol production was to have reached 9 billion gallons in 2008 and 15.2 billion gallons per year (or 1 million b/d) by 2012. From January through September 2009, the United States produced an average of 678,000 b/d of ethanol, or the equivalent of 10.4 billion gallons at an annualized rate, mainly from corn. In 2007, about 6.5 billion gallons of ethanol were produced in the United States, mainly from corn (Renewable Fuels Association 2009).

About 6 billion gallons per year (or 400,000 b/d) of ethanol are needed in the United States to replace the potentially carcinogenic gasoline additive methyl tertiary-butyl ether (MTBE). Thus, production levels of 678,000 b/d of ethanol only net about 278,000 b/d of ethanol that actually displace gasoline rather than replace MTBE, which was a natural gas-based product. Given the lower energy content of ethanol, this amounts to about 185,000 b/d of gasoline that are being displaced. This figure compares with average gasoline demand of 9 million b/d. Thus, current ethanol production is not yet significantly replacing gasoline per se, but replacing additives that are being removed from the fuel system anyway.

Various federal and state incentives have been adopted, such as blender credits and import tariffs, to promote domestic ethanol production. Currently, there are three major federal policies relevant to biofuels: an RFS; a subsidy for blending biofuel; and a tariff on imported ethanol.

The RFS and blending subsidy aim to promote the production and consumption of biofuels in the United States, while the tariff acts to restrict the import of ethanol, in effect ensuring it remains a "home-grown" fuel. In addition, there are a variety of smaller federal policies that grant money for research and development (R&D) purposes or give subsidies to various constituencies related to biofuels, such as farmers, certain ethanol producers, and gasoline station owners who install E-85 pumps.

But even the current set of policies has evolved over the past three decades. Government financial support for corn-based ethanol has a long history dating to the Energy Tax Act of 1978, which exempted fuels with at least 10 percent ethanol by volume from the excise tax on gasoline (U.S. General Accounting Office 2000). The exemption effectively subsidized ethanol by $0.40/gal. In 1980, two new options were also created, a blender's tax credit and a pure alcohol fuel credit (Solomon, Barnes, and Halvorsen 2007). While they subsidized ethanol to the same degree, they were much less frequently used. The exemption and its equivalent subsidy stayed roughly similar in nominal terms for the next 25 years, although the benefits were allowed to go to blends of less than 10 percent after the Energy Policy Act of 1992 (U.S. General Accounting Office 2000). The exemption and subsidies increased to $0.60/gal in the Tax Reform Act of 1984 before falling to $0.54/gal in 1990 and to $0.52/gal when they were canceled in 2004 (General Accounting Office 2000; Rubin, Carriquiry, and Hayes 2008).[5]

The American Jobs Creation Act of 2004 replaced the exemption and existing credits with the Volumetric Ethanol Excise Tax Credit (VEETC) that gave the credit directly to blenders (Rubin, Carriquiry, and Hayes 2008).[6] The rate of the credit was initially $0.51/gal, although it was reduced to its current level of $0.45/gal in the 2008 Farm Bill (Solomon, Barnes, and Halvorsen

[5] The amount of the subsidy was already scheduled to fall to $0.51/gal on January 1, 2005, when VEETC came into effect (Government Accounting Office 2000).

[6] VEETC replaces the previous federal ethanol excise tax incentive established by the Energy Security Act of 1979. VEETC was signed into law October 22, 2004, by President Bush and was effective as of January 1, 2005. VEETC simplifies the tax collection system; it requires that highway revenues be collected and deposited into the Highway Trust Fund (eliminating fraud complications from the previous system). Under VEETC, blenders receive a credit from general government revenues other than taxes destined for the highway trust fund, and gasoline retailers continue to collect regular gasoline taxes at the pump ("United States (Federal) Alternative Fuel Dealer; Renewable Fuels Association 2008).

2007). VEETC is authorized until the end of 2010 (U.S. Department of Agriculture [USDA], Economic Research Service 2008).

In addition to the current $0.45/gal subsidy for corn ethanol, there are other distinct subsidies for other types of biofuels: $0.50/gal for compressed or liquefied gas from biomass or biodiesel from recycled cooking oil and $1.01/gal for cellulosic ethanol (Rubin, Carriquiry, and Hayes 2008; U.S. Department of Energy [DOE], Office of Energy Efficiency & Renewable Energy 2008). A $1.00/gal credit for biodiesel from oils seeds or animal fat expired at the end of 2009, and while the House of Representatives has passed a one-year extension, it is being debated in the Senate as of the publication date of this report. The actual incidence of the subsidy and how it benefits blenders and ethanol producers depends upon relative demand and supply elasticities, a point to which we return below.

According to an Energy Information Administration (EIA) report, the United States invested $3.2 billion in tax credits to gasoline blenders in 2007. Thus, 76 percent of all funds allocated by the federal government to support all U.S. renewable energy developments, as laid out in EPAct 2005, went to gasoline blenders to support the introduction of ethanol into the transport fuel market (DOE, Energy Information Administration 2008). In addition to the blenders' subsidy, the federal government also provides for a production income tax credit, in the amount of $0.10 per gallon for the first 15 million gallons of ethanol produced annually (credit capped at $1.5 million per producer per year), to "small" ethanol producers.[7]

Additional appropriations were made to support the biofuels industry through President Barack Obama's 2009 economic stimulus package. The stimulus bill included $480 million for integrated pilot and demonstration-scale biorefineries that would produce advanced biofuels, bioproducts, and heat and power in an integrated system; $176.5 million to increase the budget for existing federal assistance for commercial-scale biorefinery projects; $110 million for fundamental research for demonstration projects, including an algal biofuels consortium; $20

[7] "Small ethanol producer" was redefined by EPAct 2005 as a plant that produces up to 60 million gallons of ethanol annually (up from 30 million gallons per year). [H.R.6]. Furthermore, a 2004 law allows farmer cooperatives to apply for the credit, and provides for offsetting against the alternative minimum tax. [Jumpstart our Business Strength (JOBS) Act, H.R.4520 (2004); also referred to as American Jobs Creation Act of 2004].

million for research related to promoting E-85 fuel and studying how higher ethanol blends (E-15 or E-20) affect conventional automobiles (DOE, Office of Energy Efficiency and Renewable Energy 2009).

The current tariff on imported fuel ethanol is $0.54/gal plus a 2.5 percent *ad valorem* tax. Ethanol from United States-Dominican Republic-Central America Free Trade Agreement (CAFTA) countries are not subject to the tariff. CAFTA countries have used duty-free access to import Brazilian hydrous ethanol and export anhydrous ethanol to the United States. Only Nicaragua has a substantial domestic ethanol industry based on domestically grown sugarcane. The Caribbean Basin Initiative (CBI) provides another way for imported ethanol to get into the country duty-free, but is only allowed to expand to a maximum of 7 percent of U.S. domestic ethanol production. Given the production cost differentials between sugarcane ethanol and corn-based ethanol, these tariffs ensure that corn-based ethanol gets the priority share of the market. Nevertheless, the potential benefits of unrestricted international trade in ethanol will be discussed later in this report.

Despite substantial efforts by the federal government to promote expanded ethanol production and use, current U.S. ethanol production is concentrated in the Midwest region; in addition, the distribution system to other parts of the country and along the coasts, where most of the nation's gasoline consumption takes place, is not well developed. This creates difficulty in expanding ethanol use in a cost-effective manner, regardless of the public funds devoted to encouraging production. Transport costs and other logistical issues prohibit many states from significantly raising consumption of ethanol. As an example regarding distribution, as of 2008 more than 1,600 E-85 ethanol fueling stations operated in over 40 U.S. states, but over one-third were in Minnesota, Iowa, and Illinois—states near major ethanol production centers (DOE 2009). We will explore the potential logistical barriers to expanded ethanol use in greater detail below.

Apart from the federal incentives to expand ethanol production and use, several states have adopted policies to promote biofuel production and consumption. For example, some states have enacted RFSs that require a greater use of ethanol-blended fuel than that required by the federal RFS (DTN Ethanol Center 2008). Other state level policies include:

- tax credits and incentive payments to retailers of ethanol-blended fuel;
- incentives for ethanol producers;
- incentives for state agencies to purchase flex-fuel vehicles (FFVs) and use E-85; and
- requirements that a percentage of gasoline sold in the state be blended with ethanol (Frisman 2006).

Four states are particularly noteworthy for the extent to which they have used such policies to promote the use of ethanol: Iowa, Illinois, Minnesota, and Wisconsin. These states were able to implement such policies because of their proximity to major corn-based ethanol producing areas.

The U.S. refining industry is attempting to address some of the logistical and economic barriers to ethanol transportation by developing alternative, renewable fuels from source material other than corn. ExxonMobil, for example, recently announced a new joint venture with Synthetic Genomics, Inc., to develop advanced biofuels from photosynthetic algae. In its brochure regarding its algae program, ExxonMobil (2009) states that "algae yield greater volumes of biofuel per acre of production than crop plant based biofuels sources. Algae could yield more than 2,000 gallons of fuel per acre of production per year" as compared to corn (about 400 gallons per acre per year) or sugarcane (600–750 gallons per acre per year). The fuel produced from the proposed process would have compatible properties to existing gasoline and diesel fuel and, therefore, could be blended directly into the existing fuel pipeline distribution system. In addition, tanks for growing the algae could be located closer to regional centers with high gasoline consumption, and algae could be grown using land and water that is not suitable for crop and food production. Chevron and other companies are also working on research to convert agricultural waste and other nonfood crops into renewable transportation fuels.

III. The Current State of Transporting Corn Ethanol in the United States

The critical determinant of whether the currently legislated U.S. biofuels targets can be achieved and sustainably maintained will be cost. Comparisons with gasoline or other fuels should include all costs, including the environmental costs of producing, storing, and consuming each fuel. In practice, such a comprehensive calculation can be very difficult to determine with any measure of accuracy. For example, if mechanisms are not in place to enforce the internalization of externalities associated with a policy like subsidized ethanol production, market prices will not reflect the full social cost of the policy.

In 2005, biofuels constituted about 3 percent of total U.S. gasoline consumption, with ethanol comprising about 2.85 percent of the gasoline pool and biodiesel comprising 0.21 percent of the diesel pool (DOE, Energy Information Administration 2007). Given existing infrastructure, the United States is starting first by maximizing domestic biorefining capacity for corn-based ethanol. This pathway to ethanol is highly criticized as costly, environmentally unfriendly, and inefficient. However, alternative fuel supporters argue that corn-based ethanol will pave the way for a more general ethanol and biofuels infrastructure and will therefore create new markets for imported sugarcane-based ethanol and other alternative fuels, including cellulosic ethanol, which will become available over time. The existence of sufficient economies of scale in production is vital to this outcome, as we will discuss below.

Ethanol has been a replacement for MTBE as an oxygenate in gasoline. MTBE was banned in most states because during the inevitable leaks in underground storage tanks of additives and fuel at any point during the pumping process, MTBE would leak into the groundwater, causing significant environmental damage. Thus, as ethanol replaces MTBE, it will naturally approach the 10 percent mandate. Notwithstanding distributional effects with respect to fuel additives, ethanol has not substantially displaced fuel imports at this juncture since the first tranche of increased ethanol production were used first and foremost to replace MTBE being removed from the gasoline additive market.

Despite strong government support, concerns exist that U.S. corn-based ethanol, now that it has managed to replace MTBE in full, will soon hit a production plateau based on the high expense of its manufacturing and transportation costs and other logistical complications, such as conflicts created by certain state environmental and blending regulations.[8]

[8] Several states have enacted regulations that require oil refiners to supply gasoline marketers with unblended gasoline, thereby allowing the marketers to blend ethanol into the fuel themselves and thereby accrue the value of

In light of the limitations to manufacturing and distributing corn-based ethanol, policymakers fashioned legislation to propel other advanced biofuels to supplement corn-based ethanol over time. The DOE aims to make cellulosic ethanol commercially viable in a conversion plant in the coming years. Scientific opinion varies regarding whether this can be achieved in such a short time frame. Moreover, existing legislation requires 250 million gallons of cellulosic ethanol to be blended into fuel supplies by 2010, but it is unlikely that this will be possible.

To produce 60 billion gallons of cellulosic ethanol at an approximate 80 gallons of ethanol per ton of dry biomass, the United States would need 750 million tons of dry biomass. At about 10 tons of biomass yield per acre of land, the United States would require 75 million acres of land to produce 60 billion gallons of ethanol. To put this into perspective, total cropland in the United States is 434 million acres and U.S.-harvested cropland is 303 million acres. Using these rule-of-thumb figures, the United States could grow the necessary biomass for fuel and still use only about 60 percent of its nonharvested cropland, but only if current biomass and ethanol yields could be expanded significantly in the coming years. An improvement in efficiency would help the case on environmental and economic fronts for ethanol.

Even with explosive expansion in ethanol production in recent years, the majority of the United States has not reached the E-10 “blending wall” level. To add insult to injury, alternative oxygenates are now being used along with ethanol, and as refining technology becomes more advanced, there will be less need for oxygenates in general. For E-10 to be a national average, some states would likely have to use more than 10 percent ethanol in their fuel and, on a practical level, this will be difficult to achieve. Only nine states in 2008 had a surplus of ethanol, and they are all located in the Midwest: North Dakota, South Dakota, Nebraska, Kansas, Minnesota, Iowa, Wisconsin, Illinois, and Indiana. Moreover, automobile manufacturers will only provide warranty guarantees for engines and parts for cars that use above ten percent ethanol in their fuel if they are FFVs or E-85 vehicles; these FFVs and E-85 cars are the only cars are able to accept a fuel that has more than 10 percent ethanol. And, even in the nine states

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credit benefits directly. These regulations are being challenged in court, and the outcome may have some impact on the amount of ethanol blended fuel that can be attained in particular states. In addition, some states have reid vapor pressure standards that might be inconsistent with the marketing of higher ethanol content fuels, including E-85.

that have an ethanol surplus, a majority of citizens do not drive FFVs or E-85 cars, nor does E-85 represent a fuel sold at a majority of retail gasoline stations throughout those states.

In 2007, the United States' domestic production of ethanol was 155,263 thousand barrels, of which 96.4 percent originated from the Midwest. By 2008, total U.S. ethanol production increased to 219,927 thousand barrels, of which 205,709 thousand barrels were from Petroleum Administration for Defense District (PADD) II in the Midwest. This production was mainly corn-based ethanol. The other 41 states did not achieve an average 10 percent blending level. In fact, as of 2008, no region of the United States was averaging as much as 10 percent ethanol average in its fuel. Even in the Midwest region, only 80 percent of the fuel had attained an average blend of 10 percent ethanol. In the Northeast, about 60 percent of the fuel attained an average of 10 percent ethanol; the South, 42 percent; the West Coast, 63 percent; and the Northwest, only 36 percent. This resulted from lack of necessary infrastructure, environmental and regulatory complications, and a shortfall of production due to plant bankruptcies and the recession.[9]

In the United States, ethanol manufacturing plants are sited near corn harvesting. There are two processes for corn processing, wet milling and dry milling, which yield different co-products.[10]

The basic goal is to obtain sugars that can be fermented to ethyl alcohol (ethanol).[11] In wet milling, the corn is conveyed to large "steep" tanks where it is soaked for 30–50 hours at 120–130° F in a dilute sulfur dioxide solution, which softens the corn kernels. The corn germ and the bran are then separated from the starch and gluten protein. The germ is used to produce oil and a

[9] In the first quarter of 2009, more than 25 biofuels facilities had closed nationwide, according to the U.S. House of Representatives' Small Business Committee. A survey of ethanol production in March 2009 found that roughly 17 percent of ethanol plant capacity stood idle. Several major ethanol producers have gone bankrupt during this period, and some facilities were purchased by major refiners such as Valero, which acquired seven ethanol plants from VeraSun Energy. The Congressional Budget Office (2009) found that ethanol producers generally break even when the prices of a gallon of gasoline is more than 70 percent of the price of a bushel of corn (or 90 percent without government existing subsidies).

[10] The descriptions are based on a document from the Minnesota Corn Growers Association, "Corn Milling, Processing and Generation of Co-products."

[11] The corn kernel contains starches, fiber, oil, and proteins; the kernel is hydrolyzed to release the starch (long chain sugars), which is further hydrolyzed into small chain sugars. The sugars are fermented, under anaerobic conditions using yeast, to produce a mixture of ethanol, solids, and water that must be separated through distillation to isolate the ethanol. The resulting ethanol must be dehydrated, and the solids (or wastes in the form of protein, fat/oil, and fiber co-products) can be recovered and used in other processes.

corn germ meal, while a corn gluten feed is produced from the bran. The starch and gluten are then separated with centrifuges. The gluten protein is concentrated and dried to form corn gluten meal, a 60 percent protein feed. The starch can be used in the food, paper, textile, and ethanol industries. To produce ethanol, the starches are mixed with water in liquefaction tanks to hydrolyze them into sugars. Sugars are then mixed with yeast for fermentation under anaerobic conditions to produce ethanol. This mixture, called the "beer," is pumped into distillation columns to separate the ethanol from the solids and water. The solids and water are separated through centrifugation into a thin stillage (waste water) and wet distillers grain. The ethanol from the distillation still contains about 5 percent water, which needs to be removed through dehydration. Finally, ethanol is denatured with a little bit of gasoline to make it unsuitable for human consumption.

In the dry milling process, corn is milled and mixed with water to form slurry. A liquefaction process follows at 180–196° F, which consists of breaking down cornstarch into dextrin (long chain sugar) with the use of enzymes. This produces a mash that is cooked to kill unwanted bacteria, cooled to 90° F, and sent to fermentation vessels where more enzymes are added to convert dextrin into dextrose (simple sugar), which will later be converted into ethanol under anaerobic conditions by yeast. The fermenting mash or beer will be distilled to separate the ethanol from the water and solids. The ethanol from the distillation still contains about 5 percent water, which needs to be removed through dehydration. The remaining solids and water are separated through centrifugation. The coarse solids collected from the centrifuge are called wet cake, and the remaining liquid is called stillage, which can be used to produce corn condensed distillers solubles and corn distillers dried grains.

Once the ethanol is produced, it is shipped to wholesale distribution centers (the so-called "rack") or to individual gasoline retail stations where the ethanol is blended into gasoline (typically E-10 or E-85 blends). Since ethanol is produced largely in the Midwest, it must be shipped at great cost by railway tank cars, tank trucks, or barge toward the coasts for blending.

Gasoline, on the other hand, is produced both in the Midwest and along the coasts near urban areas that consume the largest volumes. Gasoline is transported relatively cheaply around the

United States by refined product pipelines from refineries to distribution centers (to go onto trucks for delivery to gas stations) or directly to major industry consumers.[12] In the United States, there are an estimated 160,868 miles of liquid petroleum pipelines transporting “hazardous liquids” (mainly crude oil and refined petroleum products).[13] By contrast, no ethanol is shipped via this liquid petroleum pipeline network in the United States due to fuel quality and pipeline integrity concerns, as well as economic barriers.

There are three primary modes of transportation for ethanol: truck, rail, and barge. As of 2005, rail handled 60 percent of total ethanol transportation, trucks handled 30 percent, and barges handled 10 percent. A single rail tank car can hold around 30,000 gallons of ethanol, while a single tanker truck can only hold about 8,000 gallons of ethanol. In comparison, a single tank barge can hold around 1 million gallons. Most experts believe that rail capacity is sufficient to handle current and projected ethanol production and distribution. However, there could be substantial fixed costs in the short-to-medium term related to repairing an aging infrastructure; these costs will likely be rolled into the rates paid by consumers of rail transportation services.

Blueprints for future ethanol plants include rails, as well as the capacity to handle unit cars, as part of the design. Ethanol is currently transported in manifest rail cars, but the industry is moving toward the use of unit trains for rail transportation. Unit trains consist of about 80–100 cars all carrying the same product from source to destination and back. One obstacle with the implementation of unit trains is size. Unit trains are large and therefore require Class 1 railroad tracks, which support the heaviest loads, but only interstate rail lines are predominantly Class 1. Thus, intrastate transport will, in many cases, require new rail if it is to be of the unit train variety. There are currently only 10 locations in four U.S. states that can actually receive unit cars: California, Texas, New York, and Maryland. Thus, there may be limits as to how rapidly unit train transport can expand.

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[12] If not via pipeline, the gasoline may be imported to the United States by ship via major ports such as New York Harbor and the Port of Houston from the global market.

[13] According to the Pipeline and Hazardous Materials Safety Administration, “Liquid petroleum (oil) pipelines transport liquid petroleum and some liquefied gases, including carbon dioxide. Liquid petroleum includes crude oil and refined products made from crude oil, such as gasoline, home heating oil, diesel fuel, aviation gasoline, jet fuels, and kerosene. Liquefied ethylene, propane, butane, and some petrochemical feedstocks are also transported through oil pipelines” (U.S. Department of Transportation 2007).

Barges—while capable of transporting larger quantities than unit trains, thus delivering lower per-unit costs—are almost entirely located in the Northeast, where they handle most of the ethanol transportation in the area. Barges also move ethanol from Midwest producers down the Mississippi River to the Gulf Coast region. From there, barges can take the ethanol to Florida, as well. Barges are also used to handle Brazilian ethanol imports. Currently, barges are the fastest growing mode of ethanol transportation.

The lack of large-scale ethanol pipeline infrastructure increases distribution costs for ethanol to be used as either an additive to gasoline or as a substitute fuel. Rail, tank, and barge transport for ethanol further means that oil-based fuel is consumed in ethanol distribution, constraining the amount of gasoline, and thereby oil, that ethanol can truly displace.

Pipeline transportation has been considered vital to the future of ethanol transport for some time now, and has been researched and tested on a relatively small scale. However, questions remain about the viability of the construction of an ethanol pipeline network. At first, it was deemed impossible due to ethanol's water solubility and tendency to mix with any water present in the pipelines (water is used for cleaning pipelines and can also enter the system during fuel entry and exit). An ethanol-only pipeline could reduce the chance of water blending, at a high cost, but still there would be the risk of water contamination during ethanol transfer between modes of transportation. Furthermore, the presence of water can contribute to corrosion.

Ethanol is corrosive and can cause pipeline scouring (which could result in a perforation), and stress corrosion cracking (SCC), particularly at weld joints in pipelines, as well as in storage and transportation tanks (Association of Oil Pipe Lines and the American Petroleum Institute 2007). Scouring and SCC can drastically reduce the lifetime of a pipeline or at least require constant oversight and maintenance of the system.

The corrosive effects of ethanol have resulted in the owners of existing pipelines to, in general, be unwilling to share their facilities with a product that could possibly damage them. In order to combat these corrosive effects, industry has developed corrosion inhibitors that can be directly injected in liquid form into ethanol. While promising for the use of pipelines in general, a major drawback of the inhibitor is again the added cost; ethanol requires around 30 pounds of inhibitor per 1,000 barrels of the ethanol, and the inhibitor is priced at around $7.00 per pound.

SCC results from the entrained ambient oxygen (captured free oxygen in air) that ethanol picks up during movement between modes of transportation. SCC causes a sudden failure in the pipelines as a result of a tensile stress in a corrosive environment. Mitigation techniques include adding a different chemical agent to uptake oxygen in the ethanol (an oxygen scavenger). Hydrazine, a type of propellant used in rocket fuel, was tested because it was a good corrosion inhibitor and oxygen scavenger. However, it was found that there were too many other environmental impacts, along with the fact that it was highly toxic and dangerously unstable, that prevented hydrazine from mainstream use.

Another strike against the pipeline option is related to geography. Even if shipping the ethanol via a multiproduct pipeline becomes technically feasible, such existing infrastructure is either not in the right place or flowing in the wrong direction. Specifically, existing infrastructure mainly ships product from the South toward the Midwest instead of the opposite direction. Thus, geography and technical issues have made the ethanol pipeline transport option near impossible. One potential solution would involve the construction of a dedicated ethanol pipeline distribution network.

It should also be pointed out that Petrobras has been shipping ethanol in multiproduct pipelines for several years without adverse effects in Brazil. Special procedures are taken to separate ethanol from other products to prevent contamination. Petrobras is also investing in ethanol-only pipelines. One U.S. pipeline currently transporting ethanol successfully is Kinder Morgan's existing oil pipeline in Florida. The pipeline moves pure ethanol from Tampa Bay to Orlando to be blended with gasoline. They use a batch pipeline with ethanol and oil to protect from corrosion. But so far, the Kinder Morgan pipeline has been the exception, not the rule, and concerns about the sustained level of scaled up production has created a chicken-and-egg barrier to ethanol pipeline development and financing.

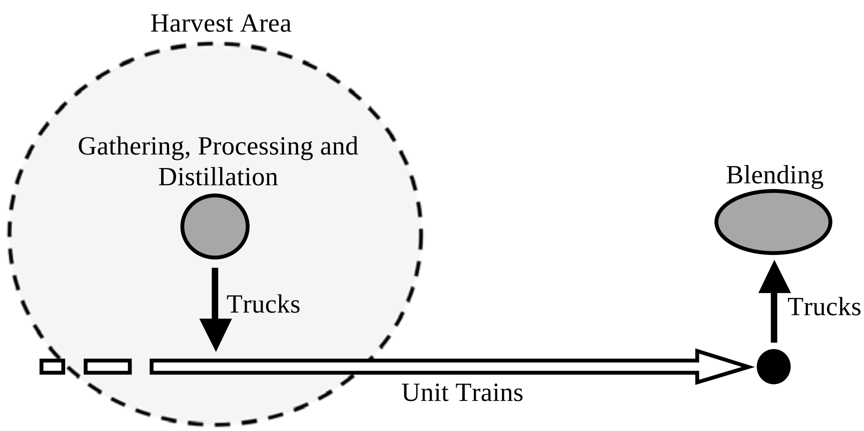
A fundamental principle of pipeline economics is scale economies. Pipelines involve huge fixed costs that are not linearly related to the volume carried. Hence, per-unit costs for transportation decline dramatically with the volume shipped. In other words, pipelines are cost effective in moving large volumes between two points. Yet, at least at this point in the development of the ethanol industry where most markets can only use E-10, there is not sufficient scale and concentration in production to justify a pipeline in most parts of the country.

IV. Ethanol Transportation Costs, Part One: A Link to Production Scale

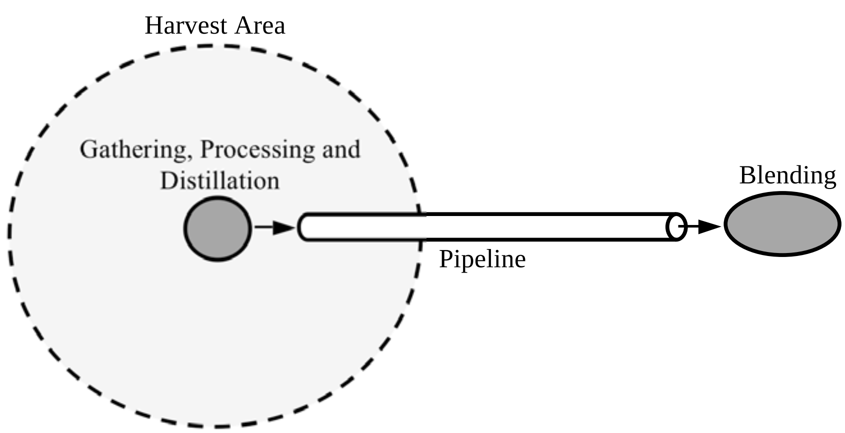
Two options for the basic structure of the ethanol "value chain" are indicated in Figure 1. The first, labeled "Trucks and Unit Trains," more closely reflects the current structure of the ethanol value chain. The second, labeled "Pipeline," is often discussed as a preferred alternative.

Figure 1: Two Possible Simplified Representations of an Ethanol Value Chain

Trucks and Unit Trains



Pipeline



Currently, most ethanol is transported via a combination of trucks and rail from the distillery to blending. This results in a total transportation cost of anywhere between $0.20 and $0.30/gal (see Table 1). Note the transport costs in Table 1 are representative only. For example, rail transport costs are differentiated by unit train, gathered cars, and single car rates and generally include a distance-based fuel surcharge. Transportation by barge (not pictured) brings some cost advantages, but the opportunities for doing so are limited by geography. The main terminals served by barge include those in Chicago, New Orleans, Houston, and Albany. While this can bring lower transport costs from the Midwest to markets in the Gulf Coast and East Coast, it does nothing for costs to markets that do not have direct water access, such as those in the West.

Table 1. Representative Distribution Costs by Mode

	Cost ($/gallon)	Volume (gallons)
… by Truck	$ 0.20	6,000
… by Rail (Unit Train)	$ 0.10	23,000
… by Barge	$ 0.05	400,000
… by Pipeline	$ 0.02	2,000,000

Source: Kinder Morgan

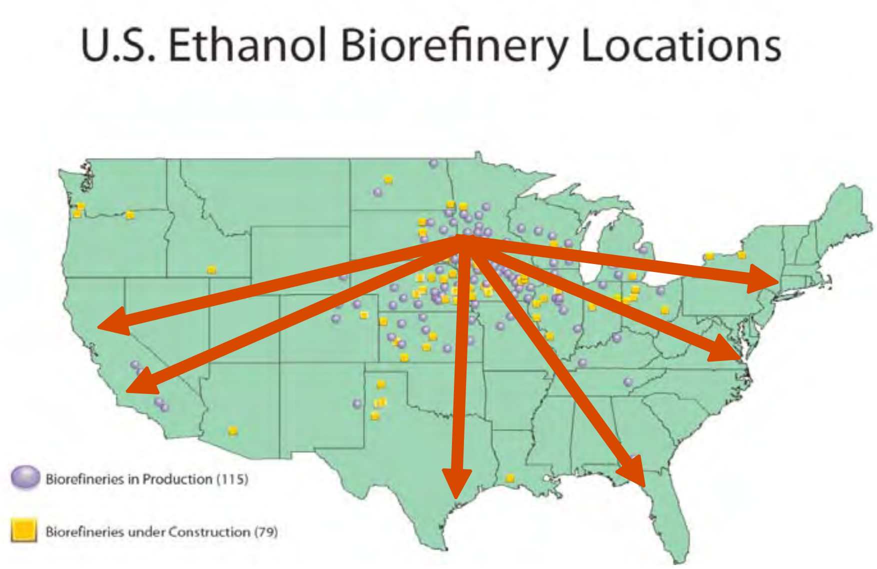
If direct connections between the distillery and the blending terminal could be facilitated by pipelines, the cost would be considerably lower, on the order of only $0.02/gal. There are currently no long-haul pipelines dedicated to the transport of ethanol. Given that most existing and planned ethanol processing and distillation occurs in the Midwest (see Figure 2), this can create large price differentials across the United States. It has been argued, therefore, that the development of pipeline capacity that could be dedicated to the transport of ethanol would drive down regional price differentials and improve the competitiveness of ethanol. The commercial viability of a pipeline, however, depends crucially on there being sufficient throughput volume to drive down cost.

Pipelines bring economies of scale, but achieving these scale economies in the transportation and distribution of ethanol may prove challenging, if it is possible at all. To begin, processing and distillation must be sufficiently large to justify the construction of a pipeline. But, the economies of scale in the production of ethanol may not be substantial enough to justify large-scale processing and distillation capacity. Urbanchuk (2008) shows that economies of scale do not exist for noncapital costs in building ethanol manufacturing facilities. The study estimates costs of noncapital inputs at around $1.68/gal for a 50 million gallons per year (MGY) facility and $1.65/gal for a 100MGY plant. Again, what is significant is not the absolute level of these costs, but rather that these costs are virtually the same, that is, independent of the scale of output. During 2003–05, corn-based ethanol plants in the United States cost roughly $1.25/gal for 48MGY capacity and $0.97/gal for 120MGY capacity, reflecting significant economies of scale.

By 2006, costs rose sharply to $1.88/gal and $1.50/gal respectively, due to the rising prices of stainless steel, copper, concrete, and contractor fees. These data imply a 20 percent reduction in the investment outlays required to build a 120MGY as compared with a 60MGY facility.

In another study, Farrell (2007) indicates that scaling production capacity up from 40MGY to 100MGY only results in a cost reduction of $0.02/gal. He reports that a 1 percent increase in capacity results in an increase of 0.84 percent in capital cost, whereas most other activities in the fuel production industries enjoy a 0.6 percent increase in capital cost, meaning ethanol production does not enjoy the same economies of scale as other industries. He notes that a primary reason for this lies in the fact that the two largest costs for an ethanol producer are the cost of the feedstock and the cost of electricity and natural gas. An ethanol producer will not enjoy any per-unit cost reductions associated with scaling up activity on these fronts, as the market rates must be paid in both cases. Generally, scaling up activity increases demand for the feedstock—which will tend to have a positive effect on price, especially if it is an industry-wide phenomenon—and diminish any scale economies.

Figure 2: Ethanol Production Facilities and Direction of Product Flow



Source: Renewable Fuels Association

If the scale economies associated with expanding production capacity are indeed minimal, the chances that investors will choose to build larger facilities are reduced, given the difficulties of amassing large amounts of biomass in one place. The prevalence of smaller-sized plants reduces the likelihood that a sufficient production volume will be amassed in a central location to justify pipeline development. In fact, recent projections by the Washington, D.C.-based Renewable Fuels Association indicate that the number of ethanol refineries will rise substantially by 2011, but the average size of production facilities will only increase slightly, rising to about 4,400 b/d (or about 67MGY). Given the relatively small scale of new developments, a gathering system would be needed to aggregate production volumes to a central location if pipeline development is to become economically viable.

A simple model will help to illustrate some important key points regarding the difficulties the ethanol industry could face when considering expansion. For the sake of exposition, we ignore the market value of the dried distillers grain used as livestock feed and other by-products. While the values associated with these products are important, their inclusion is not important for what follows, and expansion of the model to account for their values is straightforward.

Consider a firm that seeks to maximize the profits from the production and sale of ethanol, q, from corn, m. Ethanol output is a function of capacity, k, and capacity utilization, u, such that $q = uk$. Since $u \in [0,1]$, in the short run when capacity is fixed, the firm can alter u in response to changes in market variables. In the long run, by contrast, the firm will tend to adjust capacity.

Desired ethanol output determines corn input according to the rule $m = \theta(q,\pi)$, where $\theta(q,\pi)$ reflects the current state of technology and process efficiency in converting corn to ethanol as well as the process itself. According to a 2006 USDA study,

> "Corn yield per harvested acre is directly related to land quality, management, weather, farm input use, and advanced technologies used in corn production. Some of these technologies include genetically modified seed, slow release fertilizer, global positioning systems (GPS), and yield mapping."

To the extent that best-quality acreage is planted and harvested first, the ethanol yield per bushel of corn harvested could fall as production is expanded. Therefore, we let $\frac{\partial\theta}{\partial q} > 0$ and $\frac{\partial^2\theta}{\partial q^2} > 0$ reflect the fact that increasing output will require more corn input and that there may be diminishing returns to corn inputs. However, innovation in the production process can offset these negative effects, which is also indicated in the above quote. So, we let $\frac{\partial\theta}{\partial\pi} < 0$ account for technological advances in the ethanol industry.

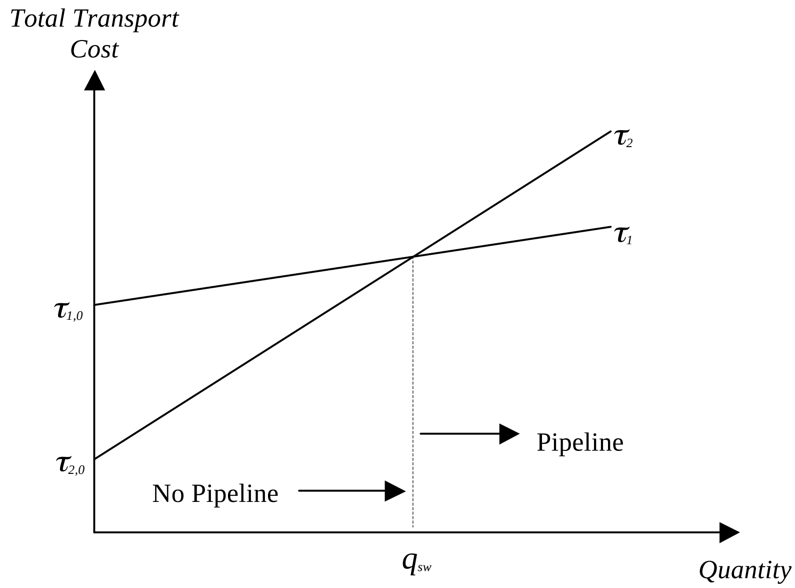
The ethanol producer receives a netback price, p, for its output. The netback price is the price received from the blender, p_b, less transportation costs from the producer to the blender, or $p = p_b - \tau$. The firm takes the price paid by the blender as given, but has some influence over the transportation cost. In particular, as discussed above, ethanol can be transported to the blender in multiple ways. For the sake of exposition we consider only two such methods here, but the problem can be generalized to incorporate others. Consider two methods: (1) low fixed cost, high variable cost and (2) high fixed cost, low variable cost. If the producer chooses to ship ethanol using method 1, the total cost is τ_1. If the producer chooses to ship by method 2, the total cost is τ_2. The fixed cost of method 2, $\tau_{2,0}$, is higher than the fixed cost of the method 1, $\tau_{1,0}$. The total variable cost of transport rises with throughput in both cases, but the marginal cost of option 1, α_1, is lower than the marginal cost of the option 2, α_2. Thus, there is a quantity, q_{sw}, at which the cost of the two options is equal, but above and below that quantity they are not. Thus, transport costs from the distillery to the blender are given as

$$\tau(q) = \begin{cases} \tau_{1,0} + \alpha_1 q & \text{if } q \leq q_{sw} \\ \tau_{2,0} + \alpha_2 q & \text{if } q > q_{sw} \end{cases}$$

where $\tau_{i,0} > 0$, $\alpha_i > 0$, $\tau_{1,0} < \tau_{2,0}$, and $\alpha_1 > \alpha_2$.

Thus, there is a tradeoff between fixed and variable costs when choosing the mode of transportation. Specifically, it will only make sense to bear the higher fixed costs of transport via pipeline if q is sufficiently large (see Figure 3). Notably, the average cost of option 2 is lower than the average cost of option 1 for all $q > q_{sw}$.

Figure 3: Transport Costs Comparison (Two Modes)



The conversion of corn into ethanol also requires energy, e. Energy is required to generate steam to liquefy corn starch and produce heat to distill alcohol and dry the distillers grains. Typically, natural gas is used. In fact, natural gas costs represent the second largest expense, after corn, at many ethanol plants. Energy requirements are a function of corn input and the energy intensity of the conversion process, ϕ_e, and can be expressed as $e = \phi_e m$. Thus, better energy efficiency, captured by a decline in ϕ_e, would reduce the amount of energy required per unit corn input.

In addition, other variable factors, v, such as enzymes and catalysts, are required to produce ethanol from corn. Accordingly, variable input requirements are a function of corn inputs and a parameter reflecting technology and conversion efficiency, ϕ_v, such that $v = \phi_v m$. So, for example, better catalysts will result in fewer variable inputs.

If an ethanol distillery is to expand production, the harvest area must expand to support the flow of raw materials required to produce the desired volume of ethanol. But this will raise the cost of harvest due to costs of bulk transport.[14] In fact, according to the previously referenced 2006 USDA study,

> "The optimal location of an ethanol processing facility is largely dependent on being in close proximity to its feedstock supply, regardless of which feedstock is being utilized. This has been proven with corn-based ethanol in the United States as well as sugar-based ethanol in Brazil. Corn-based ethanol plants in the United States are located close to large supplies of corn, primarily in the Midwest, to minimize feedstock transportation costs."

Thus, we allow the cost of the harvest to be an increasing function of the amount of corn harvested, $H(m)$. Since $m=\theta(q,\pi)$, we subsume these expressions into the function $H(\cdot)$ and denote the cost of harvest as $h(q,\pi)$, where $\frac{\partial h}{\partial q}>0$ and $\frac{\partial^2 h}{\partial q^2}>0$.

The firm must pay p_m for corn, p_e for energy, and p_v for variable inputs. This allows us to express the variable cost of producing ethanol as

$$VC = p_m m + p_v v + p_e e + h(q,\pi) = (p_m + p_v\phi_v + p_e\phi_e)m + h(q,\pi),$$

where we define $\rho = p_m + p_v\phi_v + p_e\phi_e$. To keep matters relatively simple, we assume ϕ_e and ϕ_v are exogenously determined. Using the expression relating corn input to ethanol output, $m=\theta(q,\pi)$, variable cost can be written as

$$VC = \rho\theta(q,\pi) + h(q,\pi).$$

Therefore, *average* variable cost is $AVC = \left(\rho\theta(q,\pi)+h(q,\pi)\right)/q$, and it is decreasing for production levels below some q_1 and increasing otherwise.

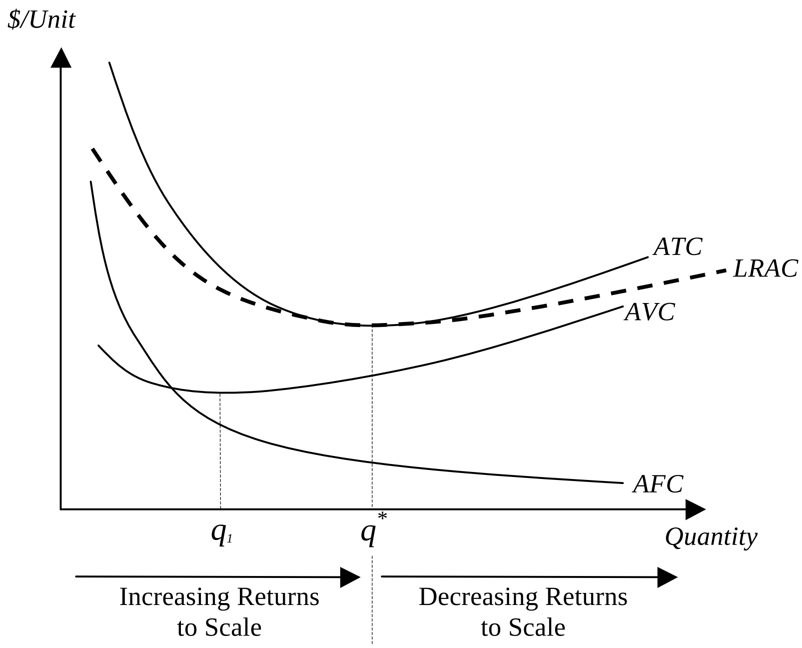
We also allow the firm to establish capacity by incurring a fixed cost which is an increasing function of capacity and the interest rate, $\bar{r}$, which we will hold fixed. For the sake of keeping

[14] The aforementioned 2006 USDA report also indicates that the cost of bulk transport is a large reason for siting ethanol distilleries near the harvest area.

things relatively simple, we express the fixed cost as an *equivalent annual cost* (EAC), such that $EAC = f(k, \bar{r})$. Average fixed cost, $AFC = f(k, \bar{r})/q$, declines as output increases.

Figure 4 depicts the *short run* average fixed cost, variable cost, and total cost for the firm. Also depicted is the *long run* average cost for the firm, which is the envelope of the short run average cost curves. It is assumed that the equilibrium shown lies at the minimum point on the long run average cost curve, which is the point at which returns to scale are constant. Accordingly, the region where $q < q^*$ is one of increasing returns to scale in production, but in the region where $q > q^*$ there are diseconomies of scale.

Figure 4: Short Run Average Fixed, Variable, and Total Cost and Long Run Average Cost with Returns to Scale



Finally, we want to allow government subsidies to influence the firm's decision, so we must allow for a rebate on production, s. In the case where the subsidy is to the blender rather than the ethanol producer, there is some incidence, I_s, of the subsidy that needs to be considered, where $I_s \in [0,1]$ and is determined by the elasticity of demand for ethanol by blenders and the elasticity of supply of ethanol by producers. In other words, the ethanol producer may only receive a fraction of the subsidy.

Figure 5: The Effect of the Subsidy on Price to the Blender and the Distiller

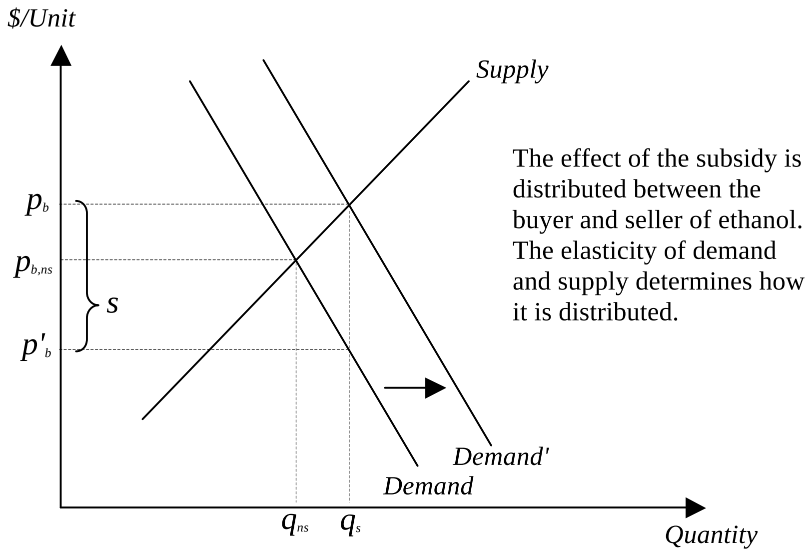


Figure 5 illustrates the issue of incidence. Specifically, the price the ethanol producer receives, p_b, is equal to the price the blender actually pays, p_b', plus the subsidy, so that $p_b = p_b' + s$. In the absence of a subsidy, the blender and producer would both see the price $p_{b,ns}$. Notice that the subsidy is generally shared between the buyer and seller. Therefore, the price that is relevant for the ethanol producer is the netback price, $p_b - \tau(q)$. But this can also be expressed as $p_{b,ns} + I_s s - \tau(q)$, or the price in the absence of a subsidy plus the portion of the subsidy received, minus the transport cost.

Taking all of the above into account, the firm will seek to maximize profits from the production of ethanol. However, it must first determine how much capacity to install for this purpose. When determining the size of the facility to be constructed, the firm must make some assessment regarding its operating parameters. Specifically, the firm will assume a particular rate of utilization, say $\bar{u}$, which may be an expected long-run rate of utilization. It will also take output and input prices as given. Thus, when choosing plant size, the firm's problem can be posed as:

$$\max\ pq - VC - EAC$$

subject to the constraints:

$$q = \bar{u}k$$

$$m = \theta(q, \pi) \text{ where } \frac{\partial \theta}{\partial q} > 0 \text{ and } \frac{\partial^2 \theta}{\partial q^2} > 0,$$

$$VC = \rho\theta(q, \pi) + h(q, \pi),$$

$$EAC = f(k, \bar{r}) \text{ where } \frac{\partial f}{\partial k} > 0 \text{ and } \frac{\partial^2 f}{\partial k^2} > 0,$$

$$\text{and } p = p_{b,ns} + I_s s - \tau(q).$$

Making use of the constraints, the firm's problem, with regard to its decision on capacity, becomes: $\max_k \left(p_{b,ns} + I_s s - \tau(q)\right)q - \rho\theta(q, \pi) - h(q, \pi) - f(k, \bar{r})$

which yields the following first order condition:

$$(1) \quad \frac{\partial V}{\partial k} = \left(p_{b,ns} + I_s s - \tau(q)\right)\frac{\partial q}{\partial k} - \frac{\partial \tau}{\partial q}\frac{\partial q}{\partial k}q - \rho\frac{\partial \theta}{\partial q}\frac{\partial q}{\partial k} - \frac{\partial h}{\partial q}\frac{\partial q}{\partial k} - \frac{\partial f}{\partial k} = 0.$$

Upon rearranging terms, equation (1) becomes

$$(2) \quad \underbrace{\left(p_{b,ns} + I_s s\right)\frac{\partial q}{\partial k}}_{\substack{\text{Marginal revenue} \\ \text{at blending rack}}} = \underbrace{\frac{\partial f}{\partial k}}_{\substack{\text{Marginal cost} \\ \text{of capacity}}} + \underbrace{\rho\frac{\partial \theta}{\partial q}\frac{\partial q}{\partial k} + \frac{\partial h}{\partial q}\frac{\partial q}{\partial k}}_{\substack{\text{Marginal cost of} \\ \text{variable inputs}}} + \underbrace{\frac{\partial \tau}{\partial q}\frac{\partial q}{\partial k}q + \tau(q)\frac{\partial q}{\partial k}}_{\text{Marginal transport cost}}.$$

From the left-hand side of (2), we see that an increase in capacity will generate higher revenue. However, the right-hand side of (2) also tells us that increases in capacity will raise costs. Specifically, since $\frac{\partial f}{\partial k}, \frac{\partial \tau}{\partial q}, \frac{\partial h}{\partial q}, \frac{\partial q}{\partial k} > 0$, any increase in capacity and output will also push the right-hand side of equation (2) higher. This occurs not only because the cost of capacity is increasing, but also because the firm will have to use more variable inputs and pay more for transportation.

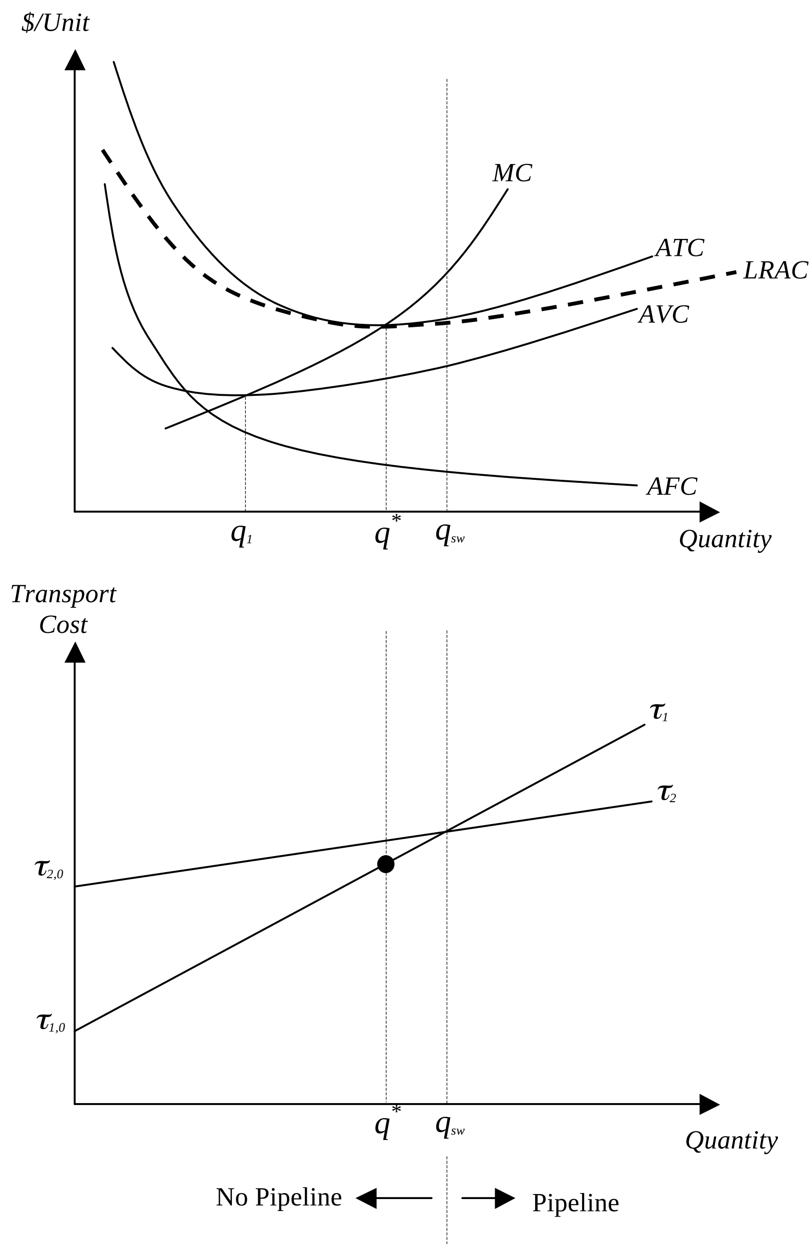
In sum, equation (2) indicates that despite the positive revenues that result from greater ethanol output, rising costs could limit the extent to which firms in the ethanol industry could profitably expand. Specifically, if marginal costs rise faster than marginal revenue, then the firm will reach a point at which it is no longer optimal to expand capacity, even if average fixed costs are declining. This result is largely driven by the fact that the firm must bear added input costs—increased harvest area and more corn, energy, enzymes, etc.—when it chooses to increase production. At some point, these added costs become prohibitive with regard to expanding capacity. Stated another way, the rents associated with production must be sufficient to pay for capacity, or

$$\underbrace{(p_b + I_s s)\frac{\partial q}{\partial k} - \rho\frac{\partial \theta}{\partial q}\frac{\partial q}{\partial k} - \frac{\partial h}{\partial q}\frac{\partial q}{\partial k} - \frac{\partial \tau}{\partial q}\frac{\partial q}{\partial k}q - \tau(q)\frac{\partial q}{\partial k} = \frac{\partial f}{\partial k}}_{\text{Rents from production}} \quad (3)$$

So, the variable q^* in Figure 6, which would be the profit-maximizing level of production that maintains the equality of equation (3), may be relatively small.

In general, similar results likely hold for firms in other industries, but a couple of crucial points may be gleaned from the exercise. One, when considering the mode of transport it is important to consider the all-in costs of ethanol production. For example, when $q^* < q_{sw}$ the construction of a pipeline to move ethanol to the blender is not the optimal outcome. This follows when ethanol output cannot be raised high enough to justify the fixed cost of a pipeline (see Figure 6). Stated another way, ATC begins to turn upward before q_{sw} is reached, so the economies of scale in ethanol production are not sufficient to warrant the expansion needed to justify construction of a pipeline.

Figure 6: Potential Economic Barriers to Ethanol Pipelines



Equation (3) also yields some insight into the effect of subsidies. A subsidy to blenders will generally increase the demand for ethanol (see Figure 6 above). If $I_s > 0$, then this should raise the netback to producers of ethanol. In the extreme case where the price elasticity of supply for ethanol is zero, $I_s = 1$ and the producer gets the full benefit of the subsidy. In any case, the improvement in the netback to the producer will in turn encourage increased ethanol production and greater capacity. If the subsidy is large enough, it is possible that production could expand such that $q^* > q_{sw}$, in which case a pipeline could be profitably constructed.

However, the story may not be so simple. Specifically, a subsidy may not have this intended first-order effect. In particular, according to the Stolper-Samuelson Theorem, increased output of ethanol should raise the price of the input that is used most intensely.[15] Thus, the subsidy, by encouraging production, could have the unintended effect of raising corn prices and even land prices, which would act as a counterweight to the first-order expansionary effect of the subsidy.

More specifically, if increased output substantially raises the price of corn and other inputs, then the marginal cost of variable inputs, $\rho \frac{\partial \theta}{\partial q}\frac{\partial q}{\partial k} + \frac{\partial h}{\partial q}\frac{\partial q}{\partial k}$, will rise, thereby diminishing the intended impact of the subsidy. In fact, if the subsidy also raises the price of land, it would further raise costs and possibly even present barriers to entry into the business of ethanol production.

The fact that input costs could increase as a result of a subsidy has substantial ramifications for policies aimed at encouraging the expansion of the ethanol industry. If subsidies ultimately raise the cost of inputs used most intensively in the targeted industry, then the subsidies may not have the desired effect, particularly if the second-order effect on input prices is substantial. Thus, the ethanol industry may be incapable of expanding significantly in its current state.

The ethanol industry might best be promoted through increased efficiency in the production process. Policies that target efficiency gains, perhaps through grants for R&D, would reduce ϕ_v, ϕ_e, and π in the model presented above, and promote expansion by lowering the marginal cost of variable inputs. Importantly, the efficiency gains would have to be substantial enough to offset any increases in the input prices that might also occur with expansion. This latter point is consistent with comments by Madson and Monceaux (2003), who state:

[15] The Stolper-Samuelson Theorem states that an increase in the price of a good will cause an increase in the price of the factor used intensively in that industry and a decrease in the price of other factors.

> "Most MFGE (motor fuel grade ethanol) producers have little control over feedstock pricing beyond hedging strategies such as trading in futures. The producers' primary edge is therefore to maximize yield."

This sentiment is reinforced by the model presented above, and, in fact, yields have been increasing since the 1980s. The question remains, however, as to how high yields must be to support substantial industry expansion, especially without subsidies.

This is also echoed by the EIA's report in the 2007 Annual Energy Outlook. Specifically:

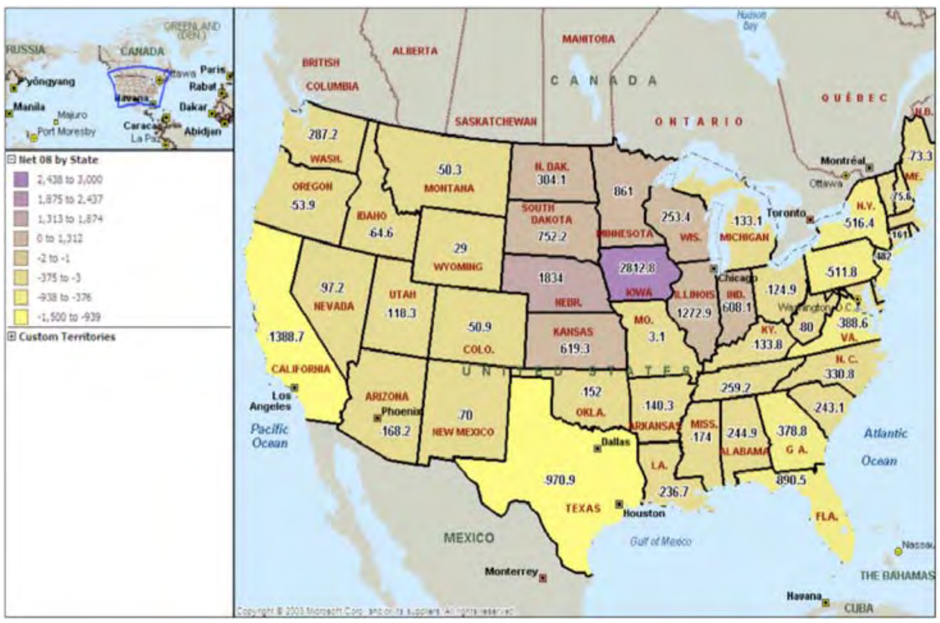
> "There have been large annual increases in yields of both corn and soybeans over the past 30 years. Corn yields increased from 86.4 bushels per acre in 1975 to 151.2 bushels per acre in 2006 … If corn yields continue to increase at the same rate (approximately 1.8 bushels per acre per year), production could increase by more than 3.1 billion bushels (29 percent) by 2030 without requiring any additional acreage … Improvements in biofuel collection and refining and bioengineering of corn and soybeans also could contribute to improved biofuel yields." (DOE, EIA 2007).

Therefore, a common theme in studying the economic viability of ethanol expansion is one of "more R&D." If advances in productivity continue, the necessity of subsidies may be diminished. Moreover, improvements in productivity could open up significant expansion opportunities that could dramatically change the manner in which ethanol is transported.

V. Ethanol Transportation Costs, Part Two: A Role for Imports

Improvements in technologies that reduce transport and manufacturing costs are vital to an ethanol industry that is to survive in a competitive landscape against other fuels and other sources of ethanol. Some of the biggest logistical difficulties facing greater ethanol penetration in the U.S. fuel supply are directly related to cost. In fact, current government support is *required* for ethanol produced in the Midwest to be an attractive option to blenders in most other parts of the country. Moreover, even with a blender credit of $0.45 and a $0.54 tariff on foreign-sourced ethanol, a large number of states are still failing to reach the 10 percent ethanol average blending level (see Figure 7). The gap between ethanol use and the 10 percent blending wall level tends to be largest in states farthest from the Midwest. Moreover, it is questionable whether or not these deficits can be efficiently eliminated over time. In particular, the farther the end use market is from the Midwest, the more the price of ethanol to the blender increases, reflecting higher transportation costs from the major producing regions (see Table 2). In addition, the *relative* price of ethanol to gasoline also increases (see Figure 8). The reason for this is twofold: not only is the price of ethanol generally higher the farther the geographic distance from the Midwest, reflecting transportation cost differentials, but conversely, the price of gasoline is generally lower along U.S. coastal regions because it is closer to gasoline production and import delivery points.

Figure 7: Ethanol Supply/Deficit Projection at E-10



Source: Kinder Morgan presentation at Baker Institute Workshop I: The Consequences of Potential Greenhouse Gas Emission Regulations for the U.S. Energy Market (August 20, 2008), available at www.bakerinstitute.org.

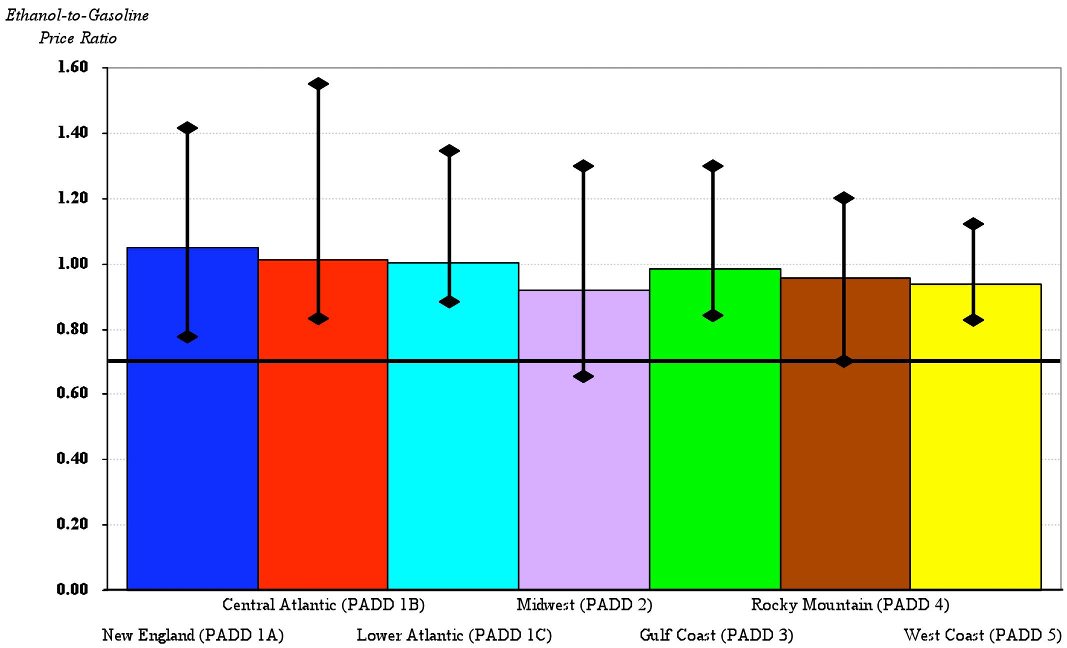
Table 2. Rail Transport Costs and Historical Average Regional Ethanol Price Differentials

	Single Car Cost	Unit Train Cost	Gathered Train Cost	Average Price Difference (2000–2009)
Rocky Mountains	$ 0.16	---	---	$ 0.12
West Coast	$ 0.27	$ 0.21	$ 0.23	$ 0.33
Gulf Coast	$ 0.26	$ 0.17	$ 0.19	$ 0.19
Lower Atlantic	$ 0.20	---	---	$ 0.17
Central Atlantic	$ 0.12	---	---	$ 0.35
New England	$ 0.13	---	---	$ 0.69

Source: Ethanol Monitor and Chicago Board of Trade (CBOT).

The relative price of ethanol-to-gasoline is important because it determines the competitiveness of the two fuels. Given that ethanol has a lower heating value than gasoline—hence yielding lower fuel efficiency—ethanol's price must be no more than roughly two-thirds of the price of gasoline to make it competitive with E-10. Thus, the closer the relative price of ethanol-to-gasoline is to one, the worse an option it becomes to blend ethanol into gasoline. This highlights the importance of location, scale, and transportation costs as ethanol competes for market share with gasoline. Given most ethanol production is in the Midwest, operations must be able to achieve sufficient volume and scale to drive down cost and/or support the construction of pipelines to lower transportation cost differentials. We also see from the values in Figure 8 that in no case is the average ethanol price purely competitive (looking at regional averages), which helps to explain the need for policies to push ethanol into the market. Even with mandates and blender credits, however, limited economies of scale and how this translates to the optimal choice for transport infrastructure (see model discussion above) may render it difficult for regions other than the Midwest to meet specified ethanol targets.

Figure 8: Historical Ethanol to Gasoline Price Ratios (2000–2009) ***(Ranges also indicated)***



Source: Ethanol Monitor and CBOT.

If meeting a specified target is the single most desired outcome for ethanol policy, then removing barriers to trade could facilitate that outcome. For example, the regions farthest from the Midwest could easily import ethanol through existing port infrastructure. Moreover, relatively low ethanol production costs in Brazil and production potential in the Caribbean and Central America could make importing ethanol a lower cost option. For example, blenders in Texas can either import ethanol via rail and truck from domestic inland locations, or they can import ethanol via ship from foreign locations. Notably, the per unit cost of transport in the latter case is much lower than the domestic local U.S. Midwest option, given relative distances and transport costs.

Currently, only a small fraction of the total amount of domestically consumed ethanol is imported (see Table 3). The current policy on ethanol imports favors supplies from Caribbean and Central American countries under the Central America Free Trade Agreement (CAFTA).[16] Specifically, up to 7 percent of U.S. domestic production can be imported from these countries without being subject to the usual tariff of $0.54/gal. This has created an "ethanol import

[16] To read more about CAFTA, see http://www.fas.usda.gov/itp/CAFTA/cafta.asp.

loophole" whereby ethanol from Brazil is imported to CAFTA countries, dehydrated, and then re-exported to the United States. While this loophole has been maligned by members of Congress from farm states, the import quantity is effectively capped. Thus, incremental ethanol imports are generally subjected to the $0.54 tariff.

Table 3. U.S. Fuel Ethanol Imports from Select Countries *(Units: Thousand Barrels)*

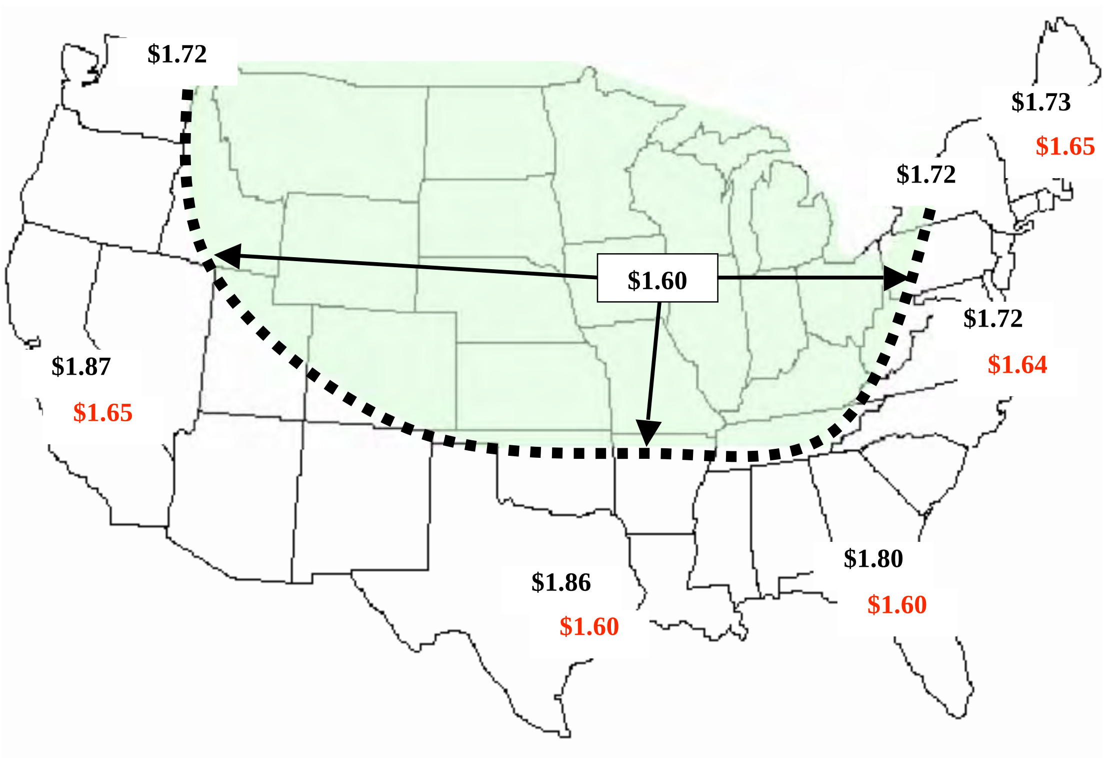
	2002	2003	2004	2005	2006	2007	2008
Brazil	0	0	2,150	743	10,326	4,495	4,835
Costa Rica	286	350	605	795	855	1,056	872
El Salvador	107	164	136	564	917	1,745	1,667
Jamaica	690	936	871	864	1,590	1,790	2,351
Trinidad & Tobago	0	0	0	238	590	1,017	1,559
Total	**1,083**	**1,450**	**3,807**	**3,214**	**15,555**	**10,148**	**12,610**

Source: U.S. EIA and Renewable Fuels Association

The degree to which open trade in ethanol could result in lower costs and facilitate goals of a nationwide attainment of 10 percent average ethanol content in fuel, or perhaps even higher, ethanol penetration is an open question. The cost of production in foreign locations and the cost of transport to various locations in the United States are important to determine to what extent imports could compete in the U.S. ethanol market. Regarding the cost of production abroad, most estimates place ethanol production costs using sugarcane as the primary feedstock at the equivalent of roughly 30 percent of the average production costs using corn as the primary feedstock. Given this, there could be substantial benefits to consumers and to broader goals of expanding the use of ethanol if barriers to trade were reduced.

Transportation costs domestically from the Midwest to coastal states are reported to vary between $0.13/gal and $0.27/gal when transport is facilitated by rail. However, as noted above, if pipeline options were available, these costs could be substantially lower. Also noted above in Table 3 is that the historical regional ethanol differential has been greatest relative to the major producing region in the New England states and varies between $0.12/gal and $0.35/gal for other PADDs (on a long-term average basis). The historical departures from the posted rail transport rates are the result of short-run constraints and should not be taken as indicative of the long-run cost differentials. In any case, even the posted rates do not beget any real advantage relative to transport costs from Brazil. In fact, the calculated ethanol freight cost for ethanol imported from Brazil is between \$0.14 and \$0.19.[17] Thus, the principle determinant for competition between imports and domestically produced ethanol shipped to the coasts should be relative production costs.

Figure 9: Where Ethanol Imports Make Sense



Note: See text and accompanying tables for explanation of results.

A simple model helps to reveal how ethanol imports from Caribbean and Latin American locations could compete in the U.S. market. The model calculations begin with the Chicago Board of Trade (CBOT) price of ethanol. The transportation rates for rail transport are applied to each region, where regions are defined at the PADD level. This yields the regional ethanol prices (given in black in Figure 9). These prices are then compared to the price of ethanol delivered from Brazil (this price includes the \$0.54 tariff and 2.5 percent *ad valorem* tax plus the freight rate for ethanol transport from Brazil). The production cost of sugar-based ethanol in Brazil is

[17] The freight cost is estimated using the difference between Free on Board (FOB) and Cost, Insurance and Freight (CIF) costs of ethanol from Brazil to the United States.

taken as $0.88/gal. The resulting prices for Brazilian ethanol delivered to the United States range from $1.60/gal to $1.65/gal, inclusive of the tariff costs.

Comparing a case with an import tariff and a U.S. blender's credit and a case without any tariff or subsidy, we see that the results are dramatically different, supporting the notion that the current tariff is effective in its protection of the domestic ethanol industry. Absent any government support, it is likely that domestic production would fall dramatically because, in that case, Brazilian imports could land economically in the U.S. coastal markets for just over $1.00/gal, representing a $0.60/gal savings over prices currently perpetuated by the tariff and *ad valorem* tax. Arguably, this would make importing and shipping gasoline blended fuels inland from the coasts using existing fuel delivery infrastructure (i.e., product pipelines) much more attractive than producing ethanol domestically in the Midwest and shipping it to coastal areas. However, with the current tariff and subsidy scheme in place, the arbitrage point lies such that expansion of the domestic ethanol industry makes sense, at least until the Midwest and Rocky Mountain States demands are met (see Figure 9). Beyond that, innovation will have to drive down production and transportation costs—which, as we saw above, are not necessarily mutually exclusive—if domestic ethanol is to compete longer term for the large coastal U.S. markets.

Feedstock and energy costs can be highly variable, so we compared several cases in which these costs were allowed to change. But in none of the cases did the answer substantially change. While the arbitrage point can move slightly, the largest fuel-consuming markets in the United States—and hence largest *potential* ethanol consuming regions—are in California, Texas, Florida, and the Northeast. The arbitrage point between ethanol produced in the Midwest and ethanol imported from Brazil (represented by the dotted lines in Figure 9) does not extend beyond these markets in any of the variants considered. In fact, for the arbitrage point to encompass the entire lower 48, thus disadvantaging imports, corn-based ethanol prices must fall by about $0.20/gal. To keep the crush spread at current levels (roughly $0.37 for corn prices at $3.50/bushel and ethanol at $1.60 on the CBOT), corn prices would have to fall just below $3.00/bushel. Of course, if the import tariff were lifted, these costs would have to fall by an even greater amount.

In sum, the coastal U.S. regions would benefit from open trade. The obvious drawback is that domestic ethanol production will be slightly lower, a result that will undoubtedly not sit well with policymakers from farm states. Nevertheless, every region of the country would be able to hit its E-10 target at a lower cost, were import tariffs to be removed.

The results indicate that imports should grow beyond the current small fraction of the total U.S. market. Moreover, imports should grow beyond those quantities that can be imported from Caribbean and Central American countries under the tariff-free quota (which amounts to 7 percent of the U.S. market) if E-10 requirements are to be met in the least-cost manner. However, production capacity in countries that could expand exports to the United States would have to grow to saturate the U.S. market. This is a difficult proposition. For foreign producers to make large-scale investments in ethanol production capability for export to the United States requires some certainty that the market will be viable. If the U.S. government intends to protect its domestic ethanol industry, then it may raise tariffs, impose quotas, increase blenders' credits, or any other myriad of possibilities. If foreign producers see this as a possibility, they will be reluctant to incur a sunk cost, which they may never recover, should domestic politics continue to point toward domestic industry protectionism.

VI. Ethanol Production Potential of Select Latin American Countries

In this section, we estimate the potential of several countries in Latin America to produce more sugarcane-based ethanol for export, possibly to the United States. The most reliable estimate is for Cuba, a country that once had a thriving sugar industry that has collapsed since the fall of the Soviet Union. The estimate in that country is based on the assumption that Cuba can revive the industry and plant areas comparable to those during the era of Soviet trade, but with yields closer to those currently being achieved in other countries in the region.

For other countries our estimate is, of necessity, a bit more uncertain because we must make assumptions about what acreage of available land can be devoted to sugarcane without detailed knowledge of whether all of the conditions for cultivation—such as temperature, water, and soil conditions—are met.[18] In addition, there is the issue of whether sugarcane cultivation can be extended without impinging on food production.[19]

Ethanol Potential in Cuba

Cuba was a major sugar producer and exporter throughout most of the twentieth century. In fact, it was a major source of U.S. sugar imports before the Cuban Revolution. Later, Cuba became the primary supplier for the Soviet Union in the 1970s and 1980s. However, with the collapse of the Soviet Union, Cuba's sugar production fell to 1.2 million metric tons (1.3 million tons) in 2007, down from 8.1 million metric tons (8.9 million tons) in 1988. Harvested acreage of sugarcane followed suit, falling from 1.45 million hectares, approximately 3.6 million acres, in 1991 and 1992 to only 400,000 hectares (about 1 million acres) in 2007. Finally, according to statistics from the Food and Agriculture Organization of the United Nations (FAOSTAT), sugarcane yields fell from 50 to 60 metric tons per hectare (t/ha), the equivalent of 22 to 27 tons per acre (tn/ac), in the 1970s and 1980s to only 28 t/ha (12.5 tn/ac) in 2007. As a result, sugar mills have been closed and large numbers of workers have been retrained and moved off the land.

Despite the past scale of the sugar industry in Cuba, if Cuba were to today choose to develop its ethanol industry, there are some questions as to how much land could be devoted to sugarcane. Cuba currently has a policy of promoting greater land use for food production. According to FAOSTAT, during the period 1970–1990, the average area harvested was 1.3 million hectares (3.2 million acres), and it may be difficult to sustain levels much higher than that. Some of the land that has been idle since the decline of the sugar industry has been converted to food crops in an effort to reduce food imports. Other land is earmarked for forest development, and there have

[18] Regarding conditions for cultivation, we are confident that our assumptions are reasonable since we are confining ourselves to countries that lie well within areas where temperatures and, for the most part, rainfall are favorable for sugarcane production. When it comes to soil conditions, sugarcane is not a demanding crop. Nonetheless, we have followed a very conservative methodology in making our projections. We give high and low estimates but our high estimates may very well be far short of these countries' capabilities.

[19] The trade-off with food production has been a contentious one of late. It should be pointed out, however, that if one or a few countries shift land from food crops to sugarcane that does not necessarily imply a reduction in world food output. Other countries might well increase food output in response to a decrease elsewhere. Indeed, it makes sense, for example, for the United States with a more temperate climate to produce corn and other food crops for export rather than to convert them into ethanol and have other countries, more suitably located, to specialize to a greater extent in the production of sugarcane for ethanol.

been recent discussions of investing in soybeans. However, given that Cuba has had a traditional comparative advantage in the production of sugar, the diversion of land to other uses may reflect the effects of economic sanctions that tend to encourage autarky where possible and promote export crops that can be sold in markets other than the United States. With the removal of the U.S.-imposed sanctions on imported ethanol, Cuba could arguably recapture its comparative advantage in sugar, which would ease the pressure to be self-sufficient in food production. Thus, acreage that has been diverted to other uses could return to sugarcane cultivation.

In Nicaragua and Brazil, growers have been getting agricultural yields of 75 to 80 t/ha (33 to 36 tn/ac) of sugarcane, and distillers have been achieving yields of 70 to 80 liters per metric ton (L/t) of sugarcane, roughly 17 to 19 gallons per ton (gal/tn). At 75 t/ha and 75 L/t (5,625 L/ha, or 600 gal/ac), Cuba would need 1.33 million hectares (3.3 million acres) to produce 2 billion gallons of ethanol. Moreover, agricultural productivity is continually improving as new plant varieties and new cultivation practices are developed through research and innovation. In some regions of Brazil, yields of 84 t/ha (37 tn/ac) and 82 L/t (20 gal/tn) of sugarcane (6,888 L/ha, or 750 gal/ac) have been achieved, and even higher yields have been achieved in some areas of São Paulo. If similar yields were reached in Cuba, ethanol production could reach 2 billion gallons with only 1.1 million hectares (2.8 million acres) of harvested land.

These production targets are ambitious and cannot be attained in a short period of time. For one, increasing the land acreage devoted to sugarcane will take time and substantial investment. The land has been neglected, and much of it has suffered from compaction with the use of very heavy Soviet built harvesting machinery (Pollitt 2004). So, the land will have to be newly planted with sugarcane. Beyond that, harvesting machinery has not been maintained, so much of that equipment will likely have to be replaced.

Downstream of harvest, significant investment is also required. Many sugar mills have been closed and those that remain have not been properly maintained (Perez-Lopez 2003; Mesa-Lago 2005). Cuba will have to undertake significant investments in distillation, transportation, storage, and distribution infrastructure if it is to produce substantial levels of ethanol. It is likely that the scale of investment necessary will run well into the billions of dollars.

Cuba has opened the door to foreign investment in the ethanol sector and may have a future partner in Brazil. Specifically, Brazil has expressed interest in sharing its expertise with other ethanol producers in order to promote the development of an active and liquid ethanol market. There are also indications that Havana is considering opening access to Cuban land to foreign companies. With flexible policies and tariff-free access to the U.S. market, Cuba would have no difficulty finding the foreign investment needed to finance the rapid development of an ethanol industry. However, current U.S. policy toward Cuba renders the likelihood of trade very low.

Ethanol Potential in Brazil

At the time of the rapid oil price increases in the 1970s, many countries, including the United States, looked at ethanol as a substitute for oil. However, when oil prices collapsed by the mid-1980s, interest waned—except in Brazil. The Brazilian government introduced Proálcool, its national alcohol program, in 1975. Today, Brazil is the world's largest ethanol exporter. However, it took Brazil many years and substantial subsidies, which have been phased out, to reach current production levels.

Brazil's approach to promoting ethanol use was to mandate that gasoline be mixed with 10 percent ethanol and that this should be increased to 25 percent by 1980 (Colares 2008). In addition, the government provided loans for the construction of ethanol plants and guaranteed the price of ethanol. Following the second oil price spike in 1980, the government required Petrobras, the state-owned oil company, to supply ethanol to filling stations. In order to promote the substitution of ethanol for gasoline, the Brazilian government also introduced subsidies for automakers for the production of vehicles that could run on E-100. The market for these cars collapsed along with oil prices in the 1980s; however, the market for vehicles using ethanol was restored in the early 2000s with the introduction of flex-fuel vehicles (FFVs) that can operate using either ethanol or gasoline. FFVs now account for roughly 85 percent of new car sales in Brazil.

One estimate puts Brazilian government subsidies from 1979 to the mid-1990s at over $16 billion in 2005 dollars.[20] Brazil is now the world's second-largest producer of ethanol with output at 6.9 billion gallons (out of world production of 20.4 billion gallons) in 2008, a significant increase from 2004 when only 3.8 billion gallons were produced. Much of the increased production has come from increasing the acreage devoted to sugarcane cultivation. But, productivity of sugarcane has also increased substantially over time, reaching an average of 65 tones/ha. In some regions in São Paulo, yields have reached 100 to 110 t/ha (45 to 49 tn/ac), representing a 33 percent increase since the mid-1970s. Plans are to increase production in São Paulo by 50 percent between 2008 and 2010.

Brazil is the largest exporter of ethanol—some 1.3 billion gallons to 48 countries in 2008. In that year, it sent about 296.2 million gallons to Jamaica, El Salvador, Trinidad and Tobago, and Costa Rica.[21] Much of this is hydrous ethanol, which is then converted to anhydrous ethanol and exported to the United States under the tariff free provisions of CAFTA.

Other Countries in Latin America and the Caribbean

Table 4 indicates the amount of agricultural land in Western Hemisphere countries that lies in the tropical zone. The Food and Agricultural Organization of the United Nations (FAO) defines agricultural area to be the sum of the following:

> "(a) arable land - land under temporary crops (double-cropped areas are counted only once), temporary meadows for mowing or pasture, land under market and kitchen gardens and land temporarily fallow (less than five years). The abandoned land resulting from shifting cultivation is not included in this category. (b) permanent crops - land cultivated with crops that occupy the land for long periods and need not be replanted after each harvest, such as cocoa, coffee and rubber; this category includes land under flowering shrubs, fruit trees, nut trees and vines, but excludes land under trees grown for wood or timber; and (c) permanent pastures - land used permanently (five years or more) for herbaceous forage

[20] Datagro, cited on p. 12 of draft conference report "Biomass to Chemicals and Fuels: Science, Technology, and Public Policy," September 25–26, 2006, Baker Institute.
[21] Brazilian Sugarcane Industry Association – UNICA.

crops, either cultivated or growing wild (wild prairie or grazing land)" (FAO Indicators Definitions).

As the data show, only a small fraction of total agricultural area is cultivated with either temporary or permanent crops. Most of the land remains as permanent pasture and meadows—suggesting the land therein is not being used very intensely.

Table 4. Land Availability and Use (2005)[22]

	Agricultural Area (1000 Ha)	**Arable Land** (1000 Ha)	**Permanent Crops** (1000 Ha)	**Permanent Meadows and Pastures** (1000 Ha)	**Sugarcane Harvested** (1000 Ha)	**Sugarcane as share of Total Ag Land**
Belize	152	70	32	50	0.0	0.0%
Brazil	263,600	59,000	7,600	197,000	5,806	2.2%
Colombia	42,557	2,004	1,609	38,944	42.6	0.1%
Costa Rica	2,895	225	330	2,340	0.0	0.0%
Dominican Rep.	3,420	820	500	2,100	85.1	2.5%
El Salvador	1,704	660	250	794	54.3	3.2%
Ecuador	7,552	1,348	1,214	4,990	93.9	1.2%
French Guiana	23	12	4	7	0.1	0.3%
Guatemala	4,652	1,440	610	2,602	190.0	4.1%
Guyana	1,740	480	30	1,230	49.0	2.8%
Honduras	2,936	1,068	360	1,508	75.9	2.6%
Jamaica	513	174	110	229	39.0	7.6%
Mexico	107,500	25,000	2,600	79,900	650.0	0.6%
Nicaragua	5,326	1,925	236	3,165	46.4	0.9%
Panama	2,230	548	147	1,535	34.9	1.6%
Peru	21,310	3,700	610	17,000	61.5	0.3%
Venezuela	21,690	2,650	800	18,240	130.7	0.6%
Totals	**489,800**	**101,124**	**17,042**	**371,634**	**7,359.5**	**1.5%**

Overall, Table 4 shows that land devoted to sugarcane is a very small share of total agricultural land, and it is even a smaller share of the land devoted to permanent crops. As noted above, it is not possible to make a precise estimate of how much additional land could be switched to sugarcane production without more knowledge of both the geography and climate conditions of various regions, as well as an accounting of the economics of alternative crops that compete with sugarcane. A shift of large amounts of acreage from one crop to another would also take time. Farmers who enter sugarcane cultivation must acquire the knowledge to grow it efficiently, and

[22] Compiled from the ResourceSTAT tool on the Food and Agricultural Organization website: http://faostat.fao.org/site/377/default.aspx#ancor.

farmers who are already growing sugarcane must acquire additional land and make investments in the equipment necessary to increase harvest. Thus, the estimates that result from the analysis that follows should be considered as the potential that could be reached within a decade, more or less.

Despite the caveats, to get some notion of what might be possible with regard to sugarcane harvest and ethanol production, we consider several scenarios. The first scenario doubles the total amount of land devoted to sugarcane in the aggregate (as opposed to in each individual country). So, while some countries might more than double such acreage, others would increase acreage devoted to sugarcane by less. Nevertheless, total acreage would increase from 7,360 thousand hectares to 14,720 thousand hectares (18 million to 36 million acres). We consider this our “low” scenario since it seems easily achievable, given sufficient time, of course. Our “medium” scenario is that countries would, in the aggregate, allocate 5 percent of total agricultural land to sugarcane, bringing sugarcane acreage to 24,490 thousand hectares (60.5 million acres). A third scenario assumes that 10 percent of agricultural land could be allocated, bringing total sugarcane acreage up to 48.9 million hectares, the equivalent of nearly 121 million acres (See Tables 4 and 5). One could consider even more ambitious shifts in land use, but the scenarios considered herein will provide an understanding of what the consequences would be if larger areas were devoted to sugarcane.

Within each of the three scenarios, we also consider two possible yield results. The low yield is 5,625 L/ha (600 gal/ac and equivalent to 75 t/ha and 75 L/t). The high yield is 6,888 liters/ha (750 gal/ac and equivalent to of 84 tons/ha and 82 liters/ton of sugarcane).

The estimates for the scenarios are given in Table 5 below and range from roughly 22 to 89 billion gallons per year. Given ethanol contains about 65 percent of the energy content of gasoline and that a barrel of oil consists of 42 gallons, these outputs translate into about 0.93 to 3.78 million b/d of crude oil equivalent. The United States alone consumes over 21 million barrels of oil a day, while Central and South America consume about 6 million b/d. All together, ethanol production from these countries could displace over 10 percent of Western Hemisphere crude oil demand.

Table 5. Estimates of Ethanol Output Potential in Latin America

	Sugarcane Acreage *(Thousands of ha)*	**Yields** *(Liters/ha)*	**Ethanol Production** *(Millions of Gallons)*
Scenario 1 Low	14,720	5,625	21,789
Scenario 1 High	14,720	6,888	26,682
Scenario 2 Low	24,490	5,625	36,252
Scenario 2 High	24,490	6,888	44,391
Scenario 3 High	48,900	5,625	72,385
Scenario 3 High	48,900	6,888	88,638

The United States could very likely meet its target of 36 billion gallons of ethanol by 2022, largely through imports from Latin America. Of course, this may discount the fact that other countries would also import Latin American ethanol. However, there are regions in Asia and Africa that also have a rich ethanol potential. Therefore, while the reality is that the United States will likely import from a number of regions—as will Europe—the bottom line is that there is sufficient ethanol production capability within the Western Hemisphere to supply most of the ethanol that the United States has mandated over at least the next decade.

Regarding the energy security emphasis of expanding ethanol production in the United States, it is worth emphasizing that imported ethanol would come largely from countries that are not current suppliers of crude oil. As a result, ethanol diversifies the U.S. energy supply portfolio and thus contributes to energy security, even though that ethanol would be imported. In addition, ethanol produced in developing countries can be an engine for growth in countries that are not endowed with conventional oil resources. Still, these benefits would have to be weighed against the risks that increased ethanol production in Latin America and the Caribbean could come at the expense of forest land or rainforest or could face political risk from worker unrest or resource nationalism.

VII. Biofuels as Alternative Energy: Net Energy Balance

If the United States is going to continue to favor domestic ethanol over cheaper, imported supplies, it is important to consider the body of evidence addressing the net energy balance of domestically produced ethanol. Questions have arisen whether the energy required to plant, produce, and transport ethanol from the U.S. Midwest is efficient or whether more fossil energy is used in producing ethanol than is gained in new ethanol supplies.

Ethanol can be produced from a variety of feedstock. We focus on corn, which at present is the basis of most U.S. production, and sugarcane, the basis of ethanol production in Brazil and potentially many other countries. The production of ethanol requires the input of energy—whether in the transportation fuel used to get biomaterials to the biorefineries or the transportation fuel to carry the final product to market; in the production of fertilizers and insecticides needed to enhance yields of the basic biomass; in the operation of the farm machinery needed to prepare the soil, produce, and finally harvest the crop; or in the operation of the biorefinery that converts the biomass to ethanol.

There has been a great deal of controversy over whether corn-based ethanol is a net contributor to energy output. Energy balance is defined as the difference between how much energy a fuel provides and how much energy it takes to create the fuel. For any alternative fuel, energy balance is often used as a metric in determining the economic cost of replacing existing fuel sources with the alternative. Studies on the energy balance of biofuels yield results ranging from positive to negative, and there is much disagreement among specialists over the methodology of published, peer-reviewed analysis.

The energy balance of a fuel varies considerably, based on its production process. Pimentel and Patzek (2005) found a negative net energy balance for ethanol produced from a variety of common U.S. feedstock, as summarized in Table 6. Interestingly, Pimentel and Patzek note that the net energy balance of ethanol made from Brazilian sugarcane is also negative.

In contrast, Wessler (2006) found a positive net energy balance for ethanol from corn, soybeans, and sunflowers and a less negative net energy balance for switchgrass and wood biomass-generated fuel. His conclusions reflect his assumption that the energy inputs used in growing feedstocks are not opportunity costs because the crops would be grown with or without an ethanol industry.

Table 6. Negative Net Energy Balance of Ethanol by Feedstock[23]

U.S. Ethanol Feedstock	Energy Balance
Soybeans	-27%
Corn	-29%
Switchgrass	-50%
Wood biomass	-57%
Sunflowers	-118%

In their July 2002 update for the USDA on corn-based ethanol, Shapouri, Duffield, and Wang (2002) show a positive net energy balance of 21,105 British thermal units (Btu)/gal and total energy consumption of 77,228 high heat value (HHV) during the production process. Their comparison of previously published methods for calculating the energy balance of corn-based ethanol highlighted how the energy balance estimates could vary from -33,562 Btu/gal to +30,589 Btu/gal.

Akinci, Gassebaum, Fitch, and Thompson surveyed the biofuels literature in 2008, finding five studies that showed a net energy balance of nearly zero for ethanol—Pimentel and Patzek were the only researchers to calculate a negative net energy balance. The authors conclude, however, that ethanol and biodiesel production do not appear sufficiently scalable to provide a significant alternative to fossil fuel consumption (Akinci et al. 2008). This finding, while not an indictment on the basis of net energy balance, is important when considering cost-effective alternatives to fossil fuels. We will return to this point below.

A canvass of biofuel studies by Farrell et al. (2006) generated similar results with regard to net energy balance. They analyzed previous studies by equalizing assumptions as much as possible and running the data through their own model, the Energy Resources Group Biofuel Analysis Meta-Model.[24] Recalculated results show that previously reported negative net energy balances for ethanol "incorrectly ignored co-products and used some obsolete data." Energy balance calculations were most sensitive to differences in accounting for the electricity generated by feedstock by-products, which was not considered in some prior studies. The authors calculated a

[23] Table from Pimentel and Patzek (2005).
[24] See http://socrates.berkeley.edu/~rael/EBAMM.

net positive energy balance for corn-based ethanol of between 4 and 9 million joules/liter (MJ/liter).[25]

While the research remains inconclusive at this point, it tends to point in the direction of saying that there is a small but positive net energy contribution for corn-based ethanol with the ratio of energy output:input in the range of 1.3 to 1.8. However, corn is a poor source of ethanol when compared with sugarcane with its energy output:input ratio of 8.3.[26] Dias de Oliveira puts the ethanol advantage much lower, with the energy efficiency ratio for corn at 1.1 and for sugarcane at 3.7. When the energy required to clean up residues left by ethanol are included, the ratios drop to 0.7 and 1.3 respectively (Dias de Oliveira 2006).

Corn is a starch that must be converted to sugar before conversion to ethanol, while sugarcane starts off as a sugar. In addition, sugarcane bagasse (the residue after the juice is extracted) can be burned to produce electricity not only for the distillery but also for export to the energy grid. Finally, as Dias de Oliveira (2006) pointed out, on a per hectare basis sugarcane produces ten times the biomass as corn.

This measure of efficiency, while interesting and relevant in some cases, should not be the sole, or even the most important, metric used to decide whether any particular source of ethanol is desirable or not. Rather, the correct criterion for deciding which biomass is viable to produce ethanol—or whether any form of ethanol itself is a viable substitute for gasoline—is to consider the relative costs and benefits of various forms of ethanol and how they compare with gasoline in terms of cost, environmental impact, and energy balance.

It is interesting to note that so much attention has been paid to the net energy balance of ethanol, especially when compared with hydrogen—a fuel that was favored early in the administration of President George W. Bush. The energy contained in hydrogen produced from natural gas is less than that in the natural gas used, thus rendering hydrogen even less attractive in its energy balance than ethanol (Morris 2005).

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[25] Note: 1 million joules = 947.8 BTU.
[26] "Beyond Science: The Economics and Politics of Responding to Climate Change." Conference report, Baker Institute for Public Policy.

The focus on energy balance reflects a concern with technical efficiency—the relationship between physical inputs and outputs. However, the cost effectiveness of converting one fuel to another is an equally, if not more, important driving factor in a market-based system, and it is this measure that should inform public policy on alternative fuels.

VIII. Biofuels as Alternative Energy: Some Environmental Issues[27]

We turn our attention in this section to a discussion of some environmental issues associated with expanded use of biofuels.

Promoting the sustainable widespread use of biofuels requires careful consideration of the potential environmental impacts of doing so. The environmental issues that give pause for concern are related to surface and ground water impacts, greenhouse gas emissions and local air pollution, and the impact of land use changes. Briefly:

- Recent research indicates that expanded use of ethanol can have deleterious effects on water quality, which follow from increases in pesticide and fertilizer runoff. Moreover, water use from irrigation is generally higher than the water demands that exist from processing oil-based fuels and will increase along with greater demand for biofuels, which can create issues related to water rights downstream of the irrigation site.
- With regard to leaks from underground storage, ethanol itself does not impose the most significant risk. Rather, potential dangers arise when ethanol is blended with gasoline in higher concentrations (greater than 10 percent by volume). Specifically, ethanol-blended gasoline can increase the size of the plumes of harmful components in gasoline such as benzene, toluene, ethylbenzene, and xylenes (BTEX), which can result in greater risk of exposure.
- Overall, greenhouse gas (GHG) emissions for biofuels, once considered lower than those for gasoline, are now uncertain due to land use changes and emissions of nitrous oxide (N_2O). It is also unclear whether local air pollution is greater or lower due to compounds hazardous to human health from biofuels.

[27] To read the full text of the environmental issues associated with expanded use of biofuels in U.S. transportation fuel, refer to Appendix I of this report.

- The environmental impacts of cellulosic ethanol (produced from feedstock such as switchgrass) tend to be smaller than those of corn-based ethanol, although there are even more uncertainties because these biofuels have not yet been commercially produced. Suggested fertilizer application rates vary widely. Water use theoretically could be zero, but some growers may choose to irrigate switchgrass to increase yields. Finally, excluding land use changes, GHG emissions are substantially lower, but certain land use changes may make cellulosic ethanol worse than gasoline.

Chemical Uses and Agricultural Practices

Meeting the mandated increased production of biofuels will inevitably result in increased agricultural activity, such as tilling more acres and higher agrichemical application. These changes will lead to adverse environmental impacts that range from local groundwater degradation to eutrophication of distant coastal waters. Runoff from nitrogen fertilizers results in the most apparent example of eutrophication, the Gulf of Mexico's "dead zone," a large area of low oxygen (hypoxia) near the mouth of the Mississippi River in which some organisms, particularly those living near the sea bed, cannot survive, leading to limited biodiversity and an altered ecosystem.

Annual row crops such as those typically used as biofuel feedstock are especially prone to cause soil erosion and nutrient runoff to surface water, with corn having one of the highest nutrient application rate and nutrient loading to surface waters. Marginal lands— which may require even greater fertilizer application and may be more susceptible to erosion and runoff—will also be pressed into agricultural service to meet the EISA mandate. This will create the potential for a substantial increase in detrimental impacts to water quality.

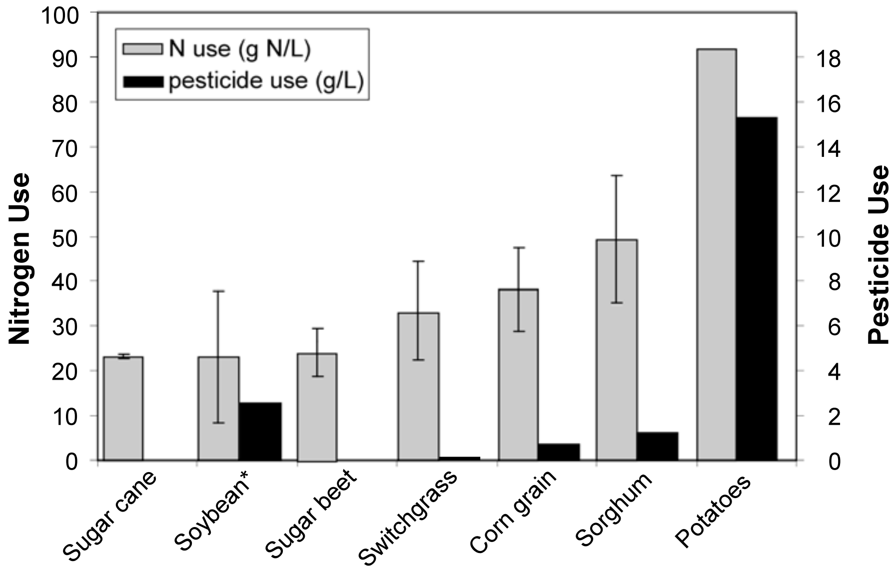
Agrichemical runoff includes both fertilizers (nitrogen and phosphorous) and chemicals designed to kill pests (herbicides, fungicides, and pesticides such as atrazine and alachlor for corn and glycophosphate, primarily for soybeans). Nitrogen and phosphorous discharge are considered some of the primary contributors to the hypoxic zone in the Gulf of Mexico, which covered over 20,000 km^2 (7,700 mi^2) in 2007. Hypoxic zones are oxygen-deficient waters, and although they are a natural incident observed to have occurred throughout geologic time, the shallow coastal hypoxic zone of the Gulf of Mexico has increased in size since the 1950s. This dead zone damages fishery resources, which can experience a decrease in species diversity along with a slump in yields. Marine species are affected by such factors as altered food supplies, forced migration, habitat reduction, and increased susceptibility to predation.

It is difficult to assess the full impact of hypoxia on Gulf fisheries because insufficient data on the effects of hypoxia on fisheries exists (Rabalais, Turner, and Wiseman 2002). However, the consensus has been that hypoxia is a detrimental ecological effect of nutrient loading in the Mississippi River Basin. Estimates for total annual freshwater costs from eutrophication are between $105 to $160 million in the United Kingdom (Pretty et al. 2003) and approximately $2.2 billion for the United States (Dodds et al. 2009), but these calculations are uncertain and do not attempt to price the impacts to saltwater areas such as the Gulf of Mexico.

Pesticides are toxic to humans as well as to other fauna. A 10-year (1992–2001) survey of U.S. streams and groundwater showed that pesticides occurred in more than 50 percent of the wells sampled in shallow groundwater and in 33 percent of deeper wells (U.S. Geological Survey [USGS] 2006). Ninety-seven percent of stream waters in agricultural areas presented pesticide compounds, and particularly high concentrations were found in the Corn Belt. The impact of these agricultural pesticides on water quality continues to be studied and is often hotly debated, but in a 2003 study, atrazine was implicated as an endocrine disruptor contributing to mutations in frogs even at very low concentrations (Hayes et al. 2003). Since pesticides are usually found as a mixture of compounds rather than individually, there is a potential for underestimating their toxicity.

Application rates of agrichemicals vary widely among crops. Figure 10 presents the application rates for nitrogen fertilizer and pesticides available for bioenergy crops in a manner that normalizes the application rates to biofuel production potential. This metric is the most important for comparisons of biofuels, and it is worth noting that sugarcane is among the lowest in terms of agrichemical application. The actual application of fertilizer on a per-acre basis is similar for sugarcane and corn, but sugarcane has a much higher net energy yield (we return to this latter point in the next section).

Figure 10: Nitrogen and Pesticide Application Rates per Unit Fuel Produced



*Note: Nitrogen and pesticide requirements for producing one liter of ethanol from different crops. Data are based on the 2003 Farm and Ranch Irrigation Survey and National Agricultural Statistics Service agricultural chemical usage datasets from the USDA. Data for pesticide application is not available for all crops. *Soybean is used for biodiesel production, and its requirements were estimated for an energy-equivalent volume of ethanol. Source: Dominguez-Faus et al. 2009.*

The increase in agriculture to meet the U.S.-mandated 15 billion gallons of fuel ethanol from corn by 2015 will require an expansion of agrichemical application, including 2.17 million metric tons (2.39 million tons) of additional nitrogen fertilizer, or about 16 percent of the nitrogen (N) fertilizer used for all crops in the United States (USDA, National Agricultural Statistics Service 2009). The high fertilizer application rates, especially for row crops in the midwestern United States, contribute an estimated 65 percent of nitrogen loads (Goolsby et al. 1999) and the greatest flux of phosphorus to local waterways and the Mississippi River basin (Powers 2007).

It is difficult to assess how much fertilizer will be used on switchgrass and the percentage of it subject to runoff because of a lack of data associated with switchgrass cultivated as a cash crop The relationship between fertilizer application and increased yields is uncertain, and there is a lack of field measurements quantifying the fate of the fertilizer in the soil, air, and water after application. In areas with sufficient rainfall, Parrish and Fike (2005) found annual sustainable switchgrass yields of 15 t/ha (<7 tn/ac) may be achievable by applying 50 kilograms of nitrogen per hectare (kg N/ha), the equivalent of 45 pounds of nitrogen per acre (lb N/ac). Other estimates suggest that 90 kg N/ha (80 lb N/ac) would be required for switchgrass and that the fraction of the fertilizer that was lost to surface water (30 percent) would be similar to corn (Miller, Landis, and Theis 2007). Powers, Ascough, and Nelson (2008) assumed a much higher average fertilization rate for switchgrass grown in Iowa—0 kg N/ha in year 1 to 260 kg N/ha (230 lb N/ac) in years 6 to 8—and predicted that the average total nitrogen loads to surface water would be 7.8 kg N/ha (7.0 lb N/ac), representing 4.2 percent of the nitrogen fertilizer applied.

Table 7 shows total annual herbicide, insecticide, and fungicide use in the United States for crops capable of being grown for biofuels. It also indicates the amount of pesticide required per liter of ethanol produced (note that the high value for potatoes is largely due to the use of sulfuric acid at harvest time to kill plant shoots to make the harvest easier).

Table 7. Pesticide Use Data[28]

Crop	*Year of data*	*Harvested area (1000 ha)*	*Total U.S. Pesticide Use*				*Pesticide Application*	
			herbicide (metric ton)	*insecticide (metric ton)*	*fungicide (metric ton)*	*other (metric ton)*	*application (kg pest./ha)*	*g pest./ L etoh*
Corn	2005	30,947	71,625	2,204	42	0	2.39	0.66
Potatoes	2005	342	634	445	2,515	30,923	100.94	15.29
Soybeans	2005	26,237	35,085	1,086	87	0	1.38	2.57
Sorghum	2003	3,426	6,995	120	0	0	2.08	1.24
Switchgrass	--	--	--	--	--	--	3.00	0.08

** *Assumed 3 kg/ha in first year, averaged over total eight-year harvest.*

Nutrient loads to the Gulf of Mexico are highly dependent on the annual rainfall in the upstream Midwest each year, total nutrient application, land usage for crops, and agricultural practices. For corn and soybean row crops, the average nitrogen discharged from the fields to surface waters through runoff, sediment transport, tile drainage, and subsurface flow represents 24 to 36 percent of the nitrogen fertilizer applied, although this fraction can range from 5 to 80 percent in extreme years of drought (e.g., 1988, 2000, Figure 11) and flooding (1983, 1993), respectively (Powers 2007). Land use and crop selection can greatly change the amount reaching surface waters. Nutrient discharges are greatest in the more humid corn and soybean regions across Illinois,

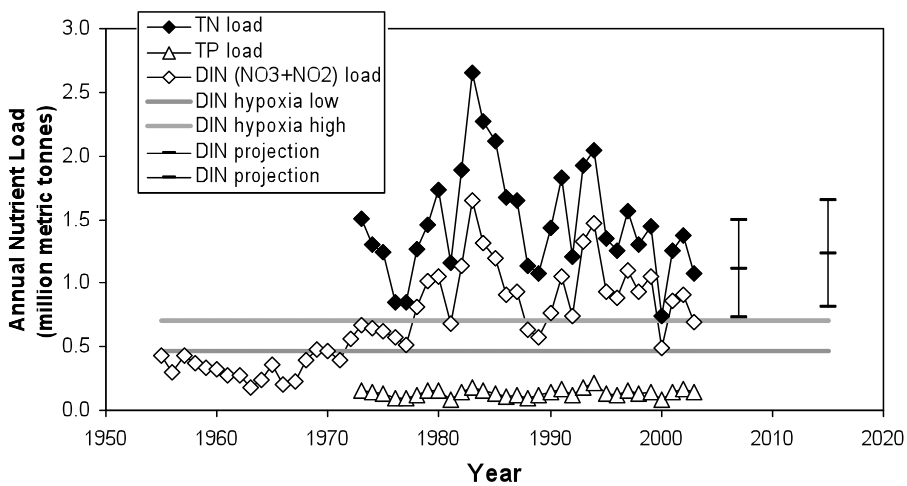
[28] The estimated pesticide application for switchgrass assumes 3 kg/ha of broadleaf herbicides (e.g., atrazine and 2,4-D) used in the first year only for switchgrass establishment.

Indiana, and Ohio (Goolsby et al. 2000; Donner, Kucharik, and Foley 2004; Burkart et al. 2006; Donner and Kucharik 2008).

The discharge of nutrients from the Mississippi River to the Gulf of Mexico has been measured by the USGS for decades (Figure 11). The total nitrogen load is comprised primarily of dissolved inorganic nitrogen (DIN), with organic and particulate nitrogen forms contributing approximately 40 percent of the total nitrogen load.

The gray lines in Figure 11 define the estimated maximum DIN export required to achieve the federal goal for reducing the Gulf of Mexico hypoxic zone to less than 5,000 km^2 (roughly 2,000 mi^2). The upper bound (0.7 million metric tons-N/y) is the federally recommended 30 percent reduction in mean DIN load, and the lower bound (0.47 million metric tons-N/y) is the 55 percent reduction in mean DIN load thought necessary to account for variability in climate and ocean dynamics. Clearly, the current DIN loads (0.94 ± 0.26 million metric tons-N/y average over the twenty year period [1984–2003]) already greatly exceed these goals.

Figure 11: Annual Nutrient Loads in the Mississippi River



Note: Annual nutrient loads at the Mississippi River St. Francis sampling point (USGS station number 07373420) near the mouth of the river (USGS 2008). The grey bars represent the goal for the range of DIN loads necessary to reduce the size of the hypoxic zone to 5,000 km (U.S. Environmental Protection Agency 2008a).

Donner and Kucharik employed a rigorous agricultural and process-based dynamic ecosystem model to predict the impact of increased corn production in the Midwest on nitrogen discharge to the Gulf of Mexico (Donner 2003; Donner and Kucharik 2003; Donner, Kucharik, and Foley 2004; Donner and Kucharik 2008). The symbols included in Figure 11 for the year 2015 are their estimates for the mean (±95 percent confidence interval) DIN exports that will result with expanded production to meet the 15 billion gallons per year corn-based ethanol goals. They predicted a 10 to 18 percent increase in DIN, further increasing the odds that these nitrogen loads will exceed the target set without significant changes in agricultural management (Goolsby et al. 2000).

There are steps that can, and likely should, be taken to reduce the problems of nutrient runoff. A variety of technological options can be used to reduce runoff, including contour farming, terraced farmland, reduced nitrogen application, grassed waterways, restored wetlands, and reduced tillage practices such as no-till or conservation tillage agriculture (Doering, Diaz-Hermelo et al. 1999; Secchi et al. 2007). Secchi et al. (2007) analyzed the costs and effectiveness of some of these methods for farms in Iowa, and it appears most cost-effective to focus attention on reducing runoff from tile-drained land (Petrolia and Gowda 2006). From a more economic perspective, nitrogen runoff would likely also be reduced with a price on nitrogen fertilizer or a system of nitrogen runoff trading between point and nonpoint sources (Ribaudo, Heimlich, and Peters 2005).

The presence of tile drainage is a very important factor in determining nutrient transport fluxes. Tile drainage involves a network of clay, concrete, or perforated plastic subsurface pipes that hasten removal of excess water, which in turn improves nutrient uptake of plant roots. A study comparing tile-drained and nondrained soils in Iowa showed that the fraction of nitrogen fertilizer lost to surface waters ranged from an average of 8 percent in nondrained fields to 36 percent in tile-drained fields (Powers, Ascough, and Nelson 2008). In the future, if tile drained lands are used predominantly for growing crops that do not require significant nitrogen fertilizer or those that are more effective at taking up the fertilizer, the nitrogen losses to surface water can be reduced.

Nutrient runoff can also be significantly reduced with no-till agriculture. In fact, no-till agriculture appears to lead to significant reductions in nutrient runoff and even larger reductions in soil loss. Comparing among feedstock on the basis of fuel energy generated, Table 8 shows model predictions for a variety of crops with both conventional tillage (CT)—in which soil is agitated in order to mix in fertilizer or other additives, form rows for plants, and remove weeds—and no-till (NT) management practices. No-till farming has been reviewed as a conservation practice as it has the potential to decrease soil erosion, use water more efficiently, and reduce soil-carbon losses, among other advantages. For the corn-soybean (CS) rotations, the no-till option reduces nutrient and soil loss relative to conventional till by 45 percent and 75 percent, respectively. The change to harvesting 50 percent of stover residue does not substantially increase nutrient runoff, and it is fine on many soils to have up to 75 percent taken away for use of biomass if no-till methods are used. However, even with no-till agriculture, the runoff from corn-based ethanol is still about five times larger than switchgrass (SG) on an energy normalization basis.

There are many potential crops that could be considered as biomass resources for future biofuel production. The decision of which crops to promote should consider geographic differences. For example, crops with higher nutrient losses to surface waters should be discouraged from areas with tile drainage, and crops with high water demands should be grown in areas where rainfall, rather than irrigation, can meet most of the water needs.

Table 8. Modeled Nutrient Losses and Soil Erosion for Energy Crop Scenarios when Normalized by Energy Content[29]

Summary	*g/MJ fuel TN/energy*	*g/MJ fuel TP/energy*	*t/MJ fuel soil/energy*
Corn (CSCT)	0.37	0.050	0.109
Corn (CSNT)	0.27	0.034	0.028
Soy (CSCT)	2.28	0.308	0.671
Soy (CSNT)	1.55	0.192	0.159
Stover 50% (CSNT)	0.028	0.004	0.010
SG	0.065	0.037	0.016

Notes: All values averaged over a 26-year period with soils and climate typical of eastern Iowa; CSCT/CSNT–corn soybean rotation with conventional till/no till; Stover harvest of 50 percent of available stover as part of CSNT rotation. Model assumes that no extra fertilizer is applied to replace the nutrient content of the harvested stover; SG switchgrass with increasing fertilizer rates over the crop life. Model includes two consecutive 8-year cycles.

Such impressive reductions in nutrient runoff raise the question whether no-till agriculture should be incentivized or even mandated. While pesticides are strictly regulated by the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) last amended in 1988, there are no regulations on fertilizer application and storage. The USDA Natural Resources Conservation Service (NRCS) has established nutrient management standards, which is a set of voluntary best management practices regarding the amount, source, placement, form, and timing of the application of nutrients (Dominguez-Faus et al. 2009).[30] Biofuel production in no-till agriculture is nearly identical to production when conventional techniques are used. Even absent expansion of domestic ethanol production, these agricultural practices carry environmental benefits that should be considered.

Water Demands of Biofuels from Selected Traditional Crops and Switchgrass

When discussing water use, it is important to differentiate between water withdrawals and water consumption. Water withdrawals (water taken from a source) are more easily measured, but they do not necessarily correspond with water consumption (water lost from the resource system that will be unavailable for other uses). Part of the water withdrawn for a given purpose will be consumed, while part of it will be returned to the system and available for reuse. Examples of water consumption are evaporation losses from cooling towers in power generation and

[29] Powers, Ascough et al. 2008.

[30] These standards and potential regulations are under revision since research is still undergoing on the mechanisms by which the chemicals applied to the fields can be transported to water bodies.

evapotranspiration losses from biophysical systems, such as agricultural systems. Different economic activities have different impacts on both withdrawals and depletion of water. In the United States, power generation is responsible for 39 percent of total national withdrawals, while only for 3.3 percent of total national water consumption, whereas agriculture accounts for 40 percent of total water withdrawals and for as much as 80 percent of total water consumption (Sandia National Laboratories 2006; Hutson et al. 2004; Gollehon and Quinby 2006). Any plans that involve intensification of agriculture will have important effects on intensification of water consumption. This is very relevant to biofuel policy because biofuel feedstock cultivation, usually row-crop agriculture, is the most water intensive of the stages of biofuels production by far. Water requirements for a typical sugarcane or corn ethanol refinery are around 2 to 10 liters of water per liter of ethanol produced (National Research Council 2008), while consumption (evapotranspiration) water requirements to produce enough feedstock to make one liter of ethanol in the United States range from 500 to 5,000 liters, depending on what crop is used to produce it.[31] Water consumption of corn ethanol in the United States is 1,200 liters of water per liter of ethanol (Lw/Le) (Figure 12).

In the United States, virtually all bioethanol (ethanol from biomass) currently produced is corn-based. EISA mandates that more corn ethanol must be produced until reaching a cap of 15 billion gallons (57 billion liters) annually by 2015. Meeting the mandated 15 billion gallons of fuel ethanol from corn will require 44 percent of 2007 United States corn production,[32] when corn was planted on 93.6 million acres, or about 37.9 million hectares (USDA, National Agricultural Statistics Service 2008). If the current proportion of irrigated corn (20 percent), is maintained throughout the expansion, and assuming a national average withdrawal rate for corn ethanol of 566 Lw/Le (Figure 12), 6.3 trillion liters (1.7 trillion gallons) of irrigation water will be needed

[31] Assuming a conservative volumetric water to ethanol ratio of 800 (e.g., for irrigated corn ethanol from Nebraska), and that a car can drive 16 miles on one gallon of ethanol (or 2/3 of the mileage from gasoline), this represents about 50 gallons of water per mile driven (gwpm). To illustrate the variability of the water requirement as a function of the crop used and where it is grown, this value could decrease to 23 gwpm for corn grown in Iowa, or increase to 90 gwpm if sorghum ethanol from Nebraska is used, or 115 gwpm if the sorghum is grown in Texas.

[32] Assuming current ethanol yield efficiencies (387 liters of ethanol per metric ton of corn grain) based on the biochemical transformation pathway of starches to ethanol.

for the corn used for ethanol, or about 3 percent of all irrigation water use in the U.S. in 2000.[33] This is the equivalent of 1.25 times the total water withdrawals for all uses in the state of Iowa.

But this estimate assumes expansion will happen in the best land and water conditions like those of much of the Corn Belt. The mandated ethanol expansion will not, however, be entirely met with those optimal growth conditions. Expansion is, for now, occurring in the Midwest (National Agricultural Statistics Service 2008), but while some midwestern regions can satisfy most of the agricultural water requirements with rainfall (for example, in Ohio less than 1 percent of corn grown is irrigated), other regions rely primarily on irrigation, such as in Nebraska, where 72 percent of corn grown is irrigated (Dominguez-Faus et al. 2009). Chiu, Walseth, and Suh (2009) identified a general trend in which irrigation water needs for corn ethanol increase from the East to the West and from the Midwest to the Southwest of the United States, which can be very useful at evaluating regional water impacts associated with biofuel crop expansion.

This spatial variability makes it difficult to assess the potential for increased irrigation requirements to exacerbate competition for water resources and create local water shortages. If expansion occurs in less optimal areas, water demand will be higher. A comprehensive regional analysis on this topic by Chiu, Walseth, and Suh (2009) shows that water appropriation by corn ethanol in the United States in the past three years has increased 246 percent whereas corn ethanol production has increased only 133 percent. They estimate that 6.1 trillion liters (1.6 trillion gallons) of water were necessary for the ethanol produced in 2008. By extrapolating this trend, 10.9 trillion liters (2.9 trillion gallons) of water will be needed for the corn used to meet the EISA goal of 15 billion gallons of ethanol in 2015. The new amount represents about 5.76 percent of total U.S. 2000 water irrigation withdrawals, or the equivalent to all withdrawals of individual states such as Arizona, Kansas, or New York (Table 9).

[33] Note that this figure only includes the water needed for the corn used in ethanol production, which is only projected to be 44 percent of the total crop. Therefore, total water use for corn irrigation in the United States will be roughly twice this figure.

Table 9. What Will It Take to Make Enough Corn Ethanol to Meet the EISA Mandate?

(Adapted from Dominguez-Faus et al. 2009.)

Metric	*Quantity*	*Benchmark for Comparison*
Fuel Requirement	56 billion liters ethanol (15 BGY)	7% of 2006 annual gasoline consumption
Amount of feedstock	143 million tons (5.8 billion bushels)	44% of the 2007 U.S. corn production
Land	16 million ha (39 million ac)	9% U.S cropland
Irrigation water*	6×10^{12} L (1.6×10^{12} gallons)	3.23% of 2000 irrigation water use in the United States. (Compare to 1.23 trillion gallons withdrawn per year in Iowa for all uses.)
Nitrogen Fertilizer	2.5 million metric tons (5.5×10^{12} lbs)	19% of the N fertilizer used for all crops in the United States. (~$2.2 billion)

Additionally, when compared to traditional fuels, corn ethanol and biodiesel consume significantly higher amounts of water (Table 10).

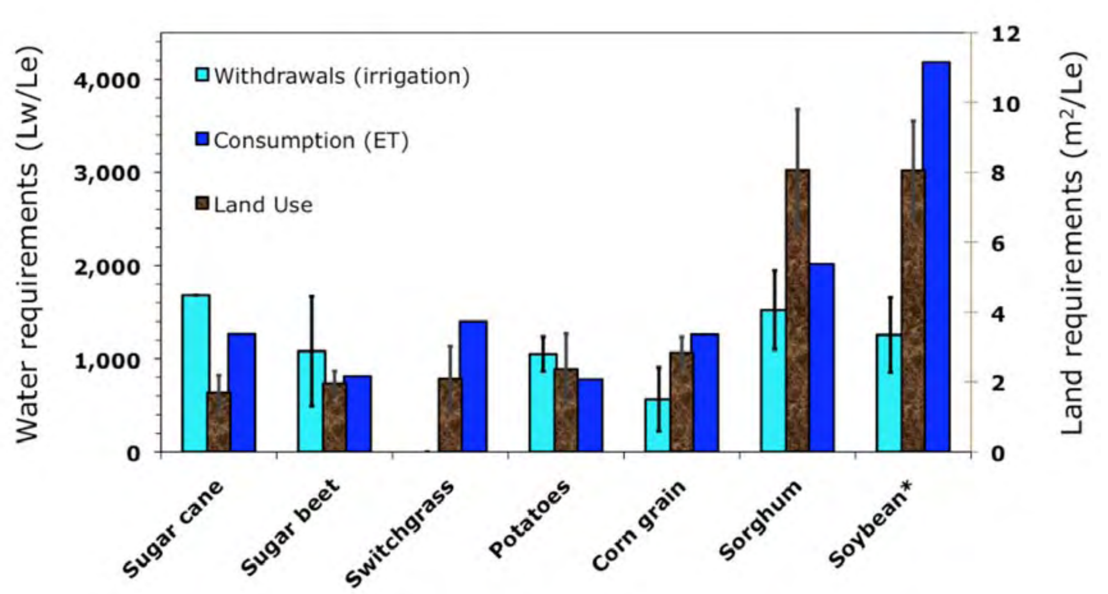
Table 10. Water Requirements for Fuel Feedstock Extraction and Processing

Process	Withdrawals L/MMBTU	Consumption L/MMBTU
Petroleum extraction	N/A	4–7[2]
Oil sands	N/A	76–185[2]
Oil shale in situ mining	N/A	4–34[2]
Oil shale surface retort	N/A	57–112[2]
Oil refining	N/A	26–68[2]
Enhanced oil recovery	N/A	49–4,716[2]
Soybean biodiesel (feedstock production)	3,322,100–6,668,100[1]	13,000–222,793[3]
Soybean biodiesel processing	N/A	4–5[2]
Corn ethanol (feedstock production)	542,500–2,072,130[1]	2,500–67,194[3]
Corn ethanol processing	373[1]	15–150[2]

[1] *Based on Dominguez-Faus et al. (2009).*
[2] *Based on Report to Congress on the Interdependency of Energy and Water (Sandia National Laboratories 2006).*
[3] *Based on Report to Congress on the Interdependency of Energy and Water (Sandia National Laboratories 2006; Chapagain and Hoekstra 2004*).

While waiting for cellulosic ethanol to be commercially viable, other traditional food crops or other feedstocks that require less water might be considered. However, most feedstocks have similar land and water footprints. Figure 12 shows water consumed (based on evapotranspiration), water withdrawn (based on irrigation), and land used to produce one liter of biofuels from several major food crops and a cellulosic feedstock. Irrigation and land use are national weighted averages of state data, with weights given according to production. It can be observed that only two crops compare favorably to corn from the water consumption point of view: potatoes and sugar beets. Even switchgrass consumes water in a magnitude similar to corn. When looking for alternative feedstock, we realize that any other major crop in the United States will use natural resources (land and water) at the same rate as corn, or even more, as is the case of sorghum and soybeans.

Figure 12: Water and Land Requirements for Different Biofuel Crops



Note: Dark blue symbols represent consumption based on evapotranspiration (ET) requirements (Chapagain and Hoekstra 2004). Light blue symbols represent withdrawals based on irrigation requirements, and brown columns represent land requirements (weighted average one standard deviation for top-producing states) (Dominguez-Faus et al. 2009). Note that soybeans are used for biodiesel production, and its water and land requirements were estimated for an energy-equivalent volume of ethanol.

Farmers irrigate when rainfall cannot meet plant water demands. For any given feedstock presented in Figure 12, the difference between consumption (ET) and withdrawals (irrigation) is indicative of the meteorological conditions of the region where it is grown. In that regard, the big difference between consumption and withdrawals of corn and soybean only indicates that they are mostly grown in the wet areas, such as most of the Midwest. Other crops that show a small gap between consumption and withdrawals, or show a higher irrigation than consumption value, such as sugarcane, sugar beets, and potatoes, will probably grow in areas where most of the water that the plant needs comes from irrigation and not from rain.

Switchgrass theoretically requires no irrigation. It could be argued that it saves water, but since it is similar in terms of consumption, its contribution to water conservation is just as limited as the other crops. The real advantage of switchgrass is its greater resistance to droughts. Droughts are abnormally dry conditions in which the water table drops temporarily. Switchgrass has a longer rooting system than corn, which means that during a drought, it will be able to reach the deeper water and survive until additional water arrives (rain or irrigation)—or at least survive longer than corn, with its shorter roots. It can also be argued that switchgrass is not irrigated because it has been relegated to marginal lands where growers have little interest in maximizing productivity. However, when switchgrass is grown as a bioenergy crop and yields need to be maximized, farmers can be expected to irrigate and fertilize.

Heightened Conflict over Water Resources

Increasing water use has the potential to exacerbate debates between states, localities, or farmers about water rights, lead to negative environmental outcomes, and worsen the impacts of droughts or more variable weather conditions. An example of a water rights argument occurred between Nebraska and Kansas. Kansas farmers alleged that Nebraska farmers used 98 billion liters (26 billion gallons) more than their allotment of the Republican River in 2004 and 2005, as stipulated in the agreement between the two states that the U.S. Supreme Court had approved in 2003 (Dominguez-Faus et al. 2009). Had farmers in Nebraska not used those 98 billion liters, they would have needed to shut off irrigation to an estimated 485,000 hectares (1.2 million acres) of farmland, or about 13 percent of the record 3.64 million hectares (9 million acres) planted in Nebraska in 2007 and 2008. Additionally, increased use of groundwater resources, which account for about 80 percent of irrigation in the Great Plains, can lead to spatial externalities in which the uptake from water from one part of an underground aquifer can make it more challenging or expensive for another user to extract water (Livingston and Garrido 2004; Gollehon and Quinby 2006). This externality could lead to more localized disagreements or problems.

In some locations, underground water sources are connected with surface wetlands that provide habitats for waterfowl and other species (Livingston and Garrido 2004). If above-ground water sources are used, certain minimum levels of water flow are needed to protect the habitat of fish (Ward and Pulido-Velazquez 2008). Climate change has the potential to exacerbate these issues, as extended periods of drought will put additional strain on the water supply.

Depending on the problem, water withdrawals and/or water consumption can be reduced, but addressing one can potentially exacerbate the other. For instance, certain technologies such as subsurface drip irrigation have been shown to reduce water withdrawals and often increase productivity (Lamm and Trooien 2003). However, drip irrigation frequently increases net water removal from water sources because less of the water returns to the original source through surface runoff or deep penetration (Ward and Pulido-Velazquez 2008). Another option for farmers is deficit irrigation, or the application of water below full requirements, but this technique can reduce yields (Fereres and Soriano 2007).

Livingston and Garrido (2004) discuss the effectiveness of the four major administrative approaches to managing groundwater—resource pricing, zoning, pumping quotas, and public buyout—using theories about institutions and four case studies from the United States and Spain. They find that it is important to establish rights to the water; one-time compensation to certain users who agree to use less water can also be effective. In contrast, they note that raising the price of water to encourage conservation is used infrequently. It can be difficult to set prices that appropriately address the negative consequences of water use. Rather, disagreements over water use are often mediated by trying to determine what the fair allocation of water is among various users, and this can be more directly addressed with extraction limits.

The water used in biofuel processing is withdrawn from local sources and can lead to disagreements in much the same way that irrigation can, even though it takes much less water to turn biomass into ethanol than is needed to irrigate crops. For instance, the local water utility refused to allow a plant proposed for Pipestone, Minn., by Cargill, Inc., because it was unable to meet the 350 million gallon/year requirement of the proposed 100 million gallon/year plant. A plant was approved in Grand Island, Neb., only after water use was reduced in an agricultural area about 15 miles away (Keeney and Muller 2006). These water requirements may fall as distilleries optimize their methods. One of many improvements under discussion is a facility that could recycle wastewater or become a “zero process water discharge” plant that keeps and reuses all wastewater (Marrone, Liberty, and Turton 2008).

Groundwater Pollution from Underground Storage Tanks

The increased use of ethanol nationwide increases the likelihood of leakage of ethanol into water supplies and the environment, often when blended with gasoline in E-10 and E-85 concentrations. Underground storage tanks commonly found in gas stations and refineries are a principal source of this contamination. These metal containers are prone to corrosion and leaking, giving rise to a nationwide problem referred to as leaking underground storage tanks (LUST). LUST is a quite common phenomenon, with over 479,000 confirmed releases, of which over 377,000 have already been cleaned up (U.S. Environmental Protection Agency 2008a). These releases can vary in magnitude from a few gallons to tens of thousands of gallons.

In order to assist remediation efforts, it is necessary to understand the unique dynamics and risks associated with LUST that release fuel that includes ethanol. Research indicates that ethanol itself is very unlikely to have strong direct adverse health and environmental consequences. In this sense it is a substantial improvement over MTBE (methyl-tert-butyl ether)—a gasoline additive that ethanol has largely replaced after MTBE was found to contaminate groundwater.

Ethanol degrades quickly in the environment through aerobic and anaerobic processes with a surface water half-life of 6.5 to 26 hours, so there is little time for people to have the chance of exposure (Ulrich 1999; Corseuil et al. 1998; Suflita and Mormile 1993; Howard et al. 1991). Even if people were to consume ethanol in its denatured form, literature on ethanol metabolism by humans indicates that environmental exposure to ethanol has minimal adverse human health impacts with no symptoms observed below 1,000 parts per million (ppm) (American Council of Governmental Industrial Hygienists 1991; Clayton and Clayton 1994).

Rather than the dangers of direct exposure to ethanol, the greater risk to human health comes from the potential for BTEX mixed with ethanol to travel farther and be more difficult to degrade (Da Silva and Alvarez 2002; Ruiz-Aguilar et al. 2002; Lovanh, Hun, and Alvarez 2002). Of the BTEX hydrocarbons, benzene is potentially the most toxic and is known to be carcinogenic. When more than 10 percent ethanol by volume is blended with gasoline (i.e., E-85), it inhibits the degradation of dangerous compounds in gasoline known as BTEX (benzene, toluene, ethylbenzene, and xylenes) that are directly damaging to human health. The BTEX-ethanol mixture should travel farther (a phenomenon referred to as plume migration) and increase the chances of exposure to more people, but overall impacts on human health are uncertain because the amount of BTEX in the E-85 is generally lower and the overall life span of the plume is shorter. In amounts of 10 percent ethanol or less, there are varying reports as to whether ethanol will extend plume migration.

Releases of ethanol will most likely lead to some altered remediation approaches and possible small-scale environmental damage. In terms of environmental impacts, ethanol can be toxic to microorganisms, and the degradation of ethanol can lead to (1) hypoxic conditions, (2) a potentially lower aqueous pH, and (3) the production of explosive methane and hydrogen gas.

A variety of factors inhibit the degradation of benzene in the presence of ethanol, which allows the benzene to spread over a wider area. Benzene biodegrades at a much faster rate under aerobic (with oxygen) rather than anaerobic (without oxygen) conditions, but the intense biodegradation of ethanol depletes the oxygen in its plume path (Alvarez and Vogel 1995; Anderson et al. 1998; Weiner and Lovley 1998a). Processes known as enzyme repression, catabolic repression, and metabolic flux dilution also inhibit the degradation of benzene. Enzyme repression occurs when the presence of the preferred substrate (ethanol) inhibits the production of the enzyme required to degrade the target pollutant, BTEX (Duetz et al. 1994; Monod 1994; Hunt et al. 1997a; Corseuil et al. 1998). Catabolic repression prevents microorganisms capable of degrading benzene from utilizing their full potential (Madigan, Martinko, and Parker 2005), and metabolic flux dilution involves carbon-limiting conditions when the utilization rate is due to the presence of ethanol that is degraded simultaneously (Egli 1995; Lovanh and Alvarez 2004). Ethanol can also inhibit anaerobic benzene degradation because ethanol depletes the available electron acceptors (sulfate, manganese [IV], iron [III], and carbon dioxide) used in anaerobic degradation (Barker et al. 1992).

In contrast to the properties that slow the degradation of benzene, ethanol does promote the growth of a wide variety of microbial populations, including those that can degrade BTEX compounds (Alvarez 1999; Cápiro et al. 2008). The proliferation of these compounds would result in faster BTEX degradation, but this positive effect of ethanol is likely to be offset by the processes mentioned above.

Previous statistical studies show benzene plume elongation in the presence of ethanol. For instance, benzene plumes resulting from regular versus E-10 gasoline spills show increased benzene plume length (an average of 36 percent) when ethanol is blended with the gasoline (Ruiz-Aguilar, O'Reilly, and Alvarez 2003). Laboratory experiments (Da Silva and Alvarez 2002; Lovanh, Hun, and Alvarez 2002; Lovanh and Alvarez 2004; Ruiz-Aguilar et al. 2002) and modeling studies (Heermann and Powers 1996; McNab, Heermann, and Dooher 1999; Molson, Barker, and Frind 2002; Gomez et al. 2008; Deeb et al. 2002) have also shown the elongation for benzene, with changes ranging from 10 percent to 150 percent. However, these studies suffered from many unknown factors influencing benzene plume length elongation, such as the age and amount of spill, hydraulic conductivity, and soil porosity.

To address this uncertainty, a new mathematical model was recently developed to evaluate plume elongation mechanisms and their relative importance (Gomez et al. 2008), and simulate plume elongation as a function of ethanol content in gasoline (Gomez and Alvarez 2009). Benzene plume lengths during the simulations showed elongations of ~60 percent for E-20 fuel ethanol blends and of ~34 percent for E-85 blends. This modeling effort concluded that plume elongation is primarily due to accelerated depletion of dissolved oxygen during ethanol degradation, a decrease in the specific BTEX utilization in a noncompetitive but simultaneous degradation of ethanol (known as metabolic flux dilution), and the repression of enzymes that degrade BTEX in the presence of ethanol (a process known as catabolite repression). Catabolite repression occurs because ethanol is a preferred source of carbon for the enzymes.

On the whole, this very likely plume elongation of BTEX could be detrimental to human health from any given spill from a LUST. However, one positive sign is that the model shows a significantly shorter life span of the benzene plume for blends with higher ethanol content: 17 years for regular gasoline, 15 years for E-10, 9 years for E-50 and 3 years for E-85. Increased microbial activity in the presence of ethanol and a lower mass content of benzene due to dilution account for the shorter life span.

The presence of ethanol in water sources can increase the risk for environmental damage. As explained above, ethanol degradation lowers available oxygen, which can be damaging to marine species living in the area of the fuel release. Ethanol also can be toxic to most microorganisms at concentrations higher than 40,000 mg/l in water by disrupting the cellular permeability barrier (Hunt et al. 1997a; Brusseau 1993; Ingram and Buttke 1984; Harold 1970). In the presence of soil, microorganisms can find some protection, increasing effective toxicity values in the field; microbial activity can occur at concentrations up to 100,000 mg/l (Araujo, Butler, and Mayfield 1998). Finally, if ethanol is degraded anaerobically, the pH of the groundwater can fall due to the production of volatile fatty acids (VFAs) such as acetic, propionic, and butyric acid ((Lasko et al. 1997; Speece 1983). Anaerobic degradation can lead to accumulation of methane or hydrogen gas, which may present a risk for explosive conditions with higher concentrations of ethanol, although no instances of issues with methane have been reported. The presence of VFAs may lead to a degradation of water quality if it leads to the reductive dissolution of metals and can contribute undesirable taste and odor to the groundwater.

Remediation for LUST occurs at a state and local level (Sekely 2009). Certain states are developing guidelines for how to deal with LUST with ethanol-blended fuels (Minnesota Pollution Control Agency 2008). States that have printed guidelines do not believe E-10 fuel will significantly alter the remediation process, and a document from the Maryland Department of the Environment (2006) concludes, “The use of ethanol as a gasoline additive will likely have minimal impact on the technology employed or the costs associated with groundwater or soil remediation."

Minnesota, a state with a significant number of E-85 pumps, is currently a leader in developing guidelines for remediation of E-85 spills. Its interim document recognizes how the degradation of BTEX can be delayed, leading to longer plume length, and it warns about the potential of methane generation from ethanol degradation that could lead to explosive conditions and the potential environmental consequences of low oxygen conditions (Minnesota Pollution Control Agency 2008). On the whole, these recommendations fit relatively well with the analysis in this report, but this work provides better quantitative assessments of the scope of the changes and a better understanding of the processes that lead to various impacts.

Greenhouse Gas Emissions Associated with Biofuels Production and Use

Ethanol production leads to emission of GHGs and more localized air pollutants such as carbon monoxide (CO) and nitrogen oxides (NOx). Older studies demonstrated that ethanol appeared to emit less GHGs than conventional gasoline. However, thorough life cycle analysis presented in more recent studies, however, that look at land use changes and the emissions of a less prevalent but more potent GHG, nitrous oxide (N_2O), question the overall reduction of GHGs from biofuels. Moreover, even the benefits of cellulosic ethanol appear questionable once land use changes are considered.

To make a proper assessment of the GHG emissions from biofuels, it is necessary to understand that emissions are generated not only as a result of the combustion of the fuel, but also at each phase of the fuel life cycle. Production, transport, and application of fertilizers, herbicides, insecticides, feedstock transportation to distilleries, biofuels conversion, and distribution all involve extensive use of fossil fuels that result in GHG emissions. These GHG emissions primarily include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). The warming potential per unit mass for each of these GHGs, which are usually expressed in CO_2 equivalents, are such that CH_4 and N_2O have GHG potentials that are 25 and 300 times of CO_2, respectively (Schlesinger 1997).

This conclusion that biofuels use is a carbon friendly alternative to conventional motor fuels is now being challenged as researchers study potential land use changes and emissions of GHGs other than CO_2. In fact, research indicates that land use changes by themselves may put the purported GHG benefits of all biofuels in doubt. On the other hand, ignoring land use changes but fully accounting for N_2O emissions would somewhat reduce but not eliminate the GHG benefits of using cellulosic ethanol. Corn-based ethanol, however, may be another story. Crutzen et al. (2007) argue that once N_2O is considered in an assessment of life-cycle GHGs of corn-based ethanol, there is likely no reduction in GHG emissions compared with conventional gasoline.

With regard to land use changes, clearing forest and grassland in order to grow biofuel feedstock results in release of carbon stored in plants and soils, either through decomposition or fire. It is estimated that worldwide, each hectare of land converted for biofuel crops results in average emissions of 351 mg of carbon dioxide equivalent. It is also estimated that the payback time for such emissions is 167 years, assuming neutral tailpipe emissions from ethanol (Fargione et al. 2008; Searchinger et al. 2008). Increasing demand for biofuels has the undesirable potential to further aggravate the already troublesome trend of clearing tropical forests in developed nations.

N_2O emissions from crops come from the nitrogen (N) in the applied fertilizer. The emissions occur both directly through nitrification and denitrification in the cropped soil and indirectly when N is lost from the cropped soil as some form other than N_2O (NOx, NH_3, NO_3) and later converted to N_2O off the farm. Estimates of in situ plus downstream N_2O emissions range from 3 to 5 percent of the N fertilizer applied (Crutzen et al. 2007).[34]

Given the potential GHG impact of expanded fuel ethanol production, the stated goal of enhancing energy security through using more biofuels must be juxtaposed with goals of addressing climate change. More specifically, if we are to attempt to justify a renewable fuels industry on the basis of lowering CO_2 emissions as the goal of policy, this seems to call into question that value of subsidizing biofuels energy production from traditional sources such as

[34] It is estimated that croplands producing soy, wheat, and corn are responsible for about 68 percent of the total N_2O emissions in the United States (Mummey et al. 1998).

corn. The ethanol industry appears to emit GHGs per unit output in equal or greater amounts when compared to the gasoline industry.

Localized Pollutant Effects Associated with Biofuels Production and Use

The effect of biofuels consumption on local air pollution is similarly uncertain. Pollutants such as carbon monoxide (CO) and nitrogen oxides (NOx) that are associated with ethanol combustion, for example, are directly harmful to human health. When compared to gasoline, these emissions are lower at the tailpipe but higher when considering the life cycle of ethanol. Thus, there may be some benefits to biofuels in terms of local air pollution in metropolitan areas where tailpipe emissions are more likely to occur and affect residents in densely populated areas, but the overall impacts are still uncertain.

As with gasoline, the burning of ethanol results in the emission of air pollutants that have negative localized impacts. For some of these pollutants—carbon monoxide, nitrogen oxides, particulate matter (PM), sulfur oxides (SOx), ozone (O_3), volatile organic compounds (VOC), and total hydrocarbons (THC)[35]—a life-cycle analysis shows that the emissions of all of these pollutants increase with ethanol, and all but one (SOx) increase with biodiesel. However, unlike GHGs, the impacts of these emissions depend on geography, so a reduction in air emissions in a densely populated area from the burning of fuels can potentially be much more important than a slight increase in life-cycle emissions.[36] This follows since some proportion of the emissions occur in less populated areas and 95 percent of the costs of air pollution are due to impacts on human health (Rabl and Spadaro 2006). When compared with gasoline, tailpipe emissions are uncertain for ethanol, although they look somewhat promising with three likely reductions (PM, CO, THC) and only one increase and uncertainty (VOC and NOx). All tailpipe emissions from biodiesel are better than conventional diesel fuel (see Table 11). It should be noted that in order to have an estimate of such emissions as close as possible to the actual values, more measurement experiments should be performed.

[35] These six are regulated by the Clean Air Act (CAA), a bill last amended in 1990 with some minor changes since then, that requires the U.S. Environmental Protection Agency (EPA) to set National Ambient Air Quality Standards (NAAQs) these common air pollutants. These six are known as “criteria pollutants” since the permissible levels of pollution are based on health and/or environmental criteria.

[36] The European ExternE project studied PM emission of less than 2.5 micrometers in France and determined that the negative impact of a unit of particulate matter emitted in Paris is an order-of-magnitude worse than highway emissions and two orders-of-magnitude worse than rural emissions (Rabl and Spadaro 2006).

Table 11. Summary of Literature of Biofuel Use Compared with Base Fuels

Pollutant	Ethanol Tailpipe	Ethanol Life Cycle	Biodiesel Tailpipe	Biodiesel Life Cycle
NOx	↑ 6–40% ↓ 30–45%	↑	↑ 12%	↑
SOx	-	↑	↓	↓
PM	↓	↑	↓ 18–71%	↑
CO	↓ 10–30%	↑ 7%	↓ 50%	↑
Ozone	-	↑	-	↑
VOC	↑ 2000%	↑ 63%	↓ 18–63%	↑
THC	↓ 10–90%	↑	↓20–76%	↑

IX. Policy Recommendations to Improve the U.S. Biofuels-Alternative Fuels Program

The United States is investing billions of dollars each year in subsidies and tax breaks to domestic ethanol producers in the hope that biofuels will become a major plank of an energy security and fuel diversification program.

However, it is our finding that not all of the mandated targets slated to be implemented under the Energy Independence and Security Act of 2007 are actually achievable in the time frames that are set forth in that legislation. We encourage Congress to revisit these mandates and revise them to be in line with realizable targets and time frames to create an improved policy that will reduce uncertainty for refiners and allow a more orderly implementation of achievable goals and mandates by the EPA. A reevaluation of the RFS must take into consideration the fact that introduction of E-85 fuel to increase the average use of ethanol into the U.S. fuel system beyond 10 percent ethanol faces major logistical problems. More realistic assessments of the penetration of E-85 must be part of the reevaluation process for RFS mandates. At present, no automobile manufacturer will extend an engine or parts warranty for vehicles that use more than 10 percent of ethanol content in fuel except for vehicles specifically designed to run on E-85 fuel. This means that the majority of cars on the road today in the United States are not under warranty for anything other than gasoline containing 10 percent ethanol or less. E-85 FFVs represented only 3 percent of the car fleet as of March 2009 and the availability of E-85 refueling stations is mainly limited to only one region of the United States. The use of E-85 or FFVs is not likely to be extensive enough to overcome the barriers to achieving the 2007 Energy Independence and Security Act of 2007 mandates for U.S. ethanol market saturation. Moreover, existing mandated targets for advanced biofuels are not currently achievable—commercially or scientifically—and need to be revisited.

Furthermore, we note that ongoing implementation of current increases in feasible renewable fuels production, such as corn-based ethanol, is coming with unintended detriments to the environment. Because ethanol is easily degraded in the environment and human exposure to ethanol itself presents minimal adverse health impacts, its role as a substitute for potentially carcinogenic gasoline additive MTBE, on balance, represents a positive development. About 6 billion gallons per year (or 400,000 b/d) of ethanol are needed in the United States to replace MTBE. However, the state and local environmental agencies responsible for site clean up must take into consideration the fact that the addition of ethanol to gasoline beyond a 10 percent concentration will impede the natural attenuation of BTEX in groundwater and soil, posing a great risk for human exposure to these toxic constituents should the fuel leak from underground storage tanks. The EPA can encourage these agencies to follow the lead of states like Minnesota, which is already releasing guidelines for E-85 remediation.

We question the scale to which ethanol can enhance U.S. energy security by replacing oil-based fuel and recommend that Congress order a cost-benefit analysis of the volume of renewable fuel being added to the American transportation fuel system versus the cost per gallon to the American taxpayer to achieve this marginal addition of non-fossil fuel based supply. We believe that such an assessment would find that the extremely high costs of implementation of this program would outweigh the indirect benefits to consumers of the small, marginal reductions in U.S. oil imports.

We also recommend that Congress and the U.S. administration refrain from crediting corn-based ethanol as receiving preferable treatment on the basis of its life-cycle greenhouse gas emissions quality. There is no scientific consensus on the climate friendly nature of U.S. produced corn-based ethanol and it is not justifiable to credit its use to reducing GHGs when compared to the burning of traditional gasoline.

Increases in corn-based ethanol production in the U.S. Midwest could cause an increase in detrimental environmental impacts, including exacerbating damage to ecosystems and fisheries along the Mississippi River and in the Gulf of Mexico and creating water shortages in some areas experiencing significant increases in fuel crop irrigation. Crops such as corn-based ethanol with higher nutrient losses to surface waters should be discouraged from areas with tile drainage, and crops with high water demands should be grown in areas where rainfall rather than irrigation can meet most of the water needs. We recommend that Congress consider mandates that would incentivize no-till agriculture as part of a sustainable renewable fuels program and that the USDA's NRCS revisit regulations on fertilizer application and storage.

Limitations in the economies of scale in ethanol production pose a significant barrier to overcoming the logistical issues that block the widespread distribution of ethanol around the United States, adding to the greenhouse gases emitted and conventional fuel burned in the transportation of ethanol to end-use markets. A lifting of the $0.54/gal tariff on imported ethanol from key countries in Central America, the Caribbean, and Latin America would allow coastal areas of the United States to be more cheaply and sustainably supplied with ethanol while at the same time help build trade and positive relations with important U.S. regional allies. We believe, on balance, that the economic and geopolitical benefits of this trade with select regional suppliers would outweigh any "energy security" costs associated with some larger percentage of U.S. ethanol supplies arriving from foreign sources.

Imported ethanol from these regions is already making its way to U.S. shores through a variety of loopholes, but at a higher cost. As discussed in this report, given the limitations of sustainable production of U.S. domestic corn-based ethanol, tariff policies that block cheaper imports are probably misguided. It is reasonable to ask if protective tariffs are meeting the goals for which they were intended and if market participants—farmers, producers, blenders, or oil refiners—are really reaping the actual profits from the tariffs.

Appendix I[37]

Introduction

Developing a sustainable national biofuels program requires careful consideration of logistical concerns (e.g., suitable production and distribution infrastructure) and of unintended environmental impacts. In this report we have reviewed the available scientific literature concerning the environmental degradation associated with the increasing biofuel demand. In particular, we have analyzed aspects of (1) air quality and greenhouse gas emissions, (2) ground and surface water quality, and (3) impacts on water and land resources availability as a result of increased biofuel demand.

Ethanol use as substitute for MTBE (methyl-tert-butyl ether) has significantly increased to meet the need for renewable fuels and the requirements of the Clean Air Act. Extensive use of ethanol in reformulated gasoline has increased its presence in gasoline- contaminated groundwater aquifers, along with other fuel components such as benzene, toluene, ethylbenzene, and xylenes (BTEX). A principal source of this contamination is underground storage tanks, a common storage solution in gas stations and refineries. These metal containers are prone to corrosion and leaking, giving rise to a nationwide problem: leaking underground storage tanks (LUST). Most of the petroleum contamination that reaches groundwater aquifers originates from these leaking storage tanks (Squillace et al. 1996), which has led to 479,000 confirmed cases of fuel release in the United States since 1985 when the Environmental Protection Agency (EPA) opened its Office of Underground Storage Tanks, with over 377,000 of them requiring some form of remediation (U.S. EPA 2008). Although fuel spills from LUST can vary in magnitude from a few gallons to tens of thousands of gallons (Nebraska Department of Environmental Quality 2005), the majority have constant low volume leaks that are hard to detect and could be present for many years before remedial action is taken. Dakhel et al. (2003) performed field experiments with small ethanol releases that indicate that groundwater impacts in these cases should be minimal. The effects of large ethanol releases from LUST have been largely unstudied (Zhang et

[37] Contributions by Pedro J. Alvarez, Joel G. Burken, Marcelo Dias de Oliveira, Rosa Dominguez-Faus, Diego E. Gomez, and Susan E. Powers.

al. 2006). We will try to shed some light on this issue by presenting the direct and indirect environmental implications of ethanol in groundwater. These implications on health and the environment will be summarized, in the context of ethanol's use as a fuel additive and its impacts on groundwater contaminant transport.

Surface water quality is primarily affected by agrichemical (pesticides and fertilizer) runoff. The most prominent effect is known as eutrophication (high levels of nutrients) of waters due to fertilizer loss from agricultural fields. Eutrophication results in algal blooms. When algae die and decay, it consumes oxygen dissolved in water, depleting it to levels as low as 2 mg/L, down from the regular levels around 8 mg/L. Under the low oxygen conditions, scientifically referred as hypoxia, life cannot be sustained. Areas undergoing this phenomenon have been called "dead zones." In the United States, the most famous dead zone is in the Gulf of Mexico, around the Mississippi River delta, which receives high nutrient loads from agricultural activity upstream in the Mississippi River basin. For this report, we have searched the scientific literature to identify to what extent energy crops and various agricultural practices have contributed to hypoxia in the Gulf of Mexico.

Another group of agrichemicals of concern are pesticides, since they are toxic to humans as well as to other fauna. A 10-year (1992–2001) survey of streams and groundwater showed that pesticides occurred in more that 50 percent of the wells sampled in shallow groundwater and in 33 percent of deeper wells. Ninety-seven percent of stream waters in agricultural areas presented pesticide compounds; particularly high concentrations were found in the Corn Belt. Since pesticides are usually found as a mixture of compounds, rather than individually, there is a potential for underestimating their toxicity. Pesticide use is strictly regulated by the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA), last amended in 1988. While there are no regulations on fertilizer application and storage, the U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) has established nutrient management standards, which is a set of voluntary best management practices regarding the amount, source, placement, form, and timing of the application of nutrients (Dominguez-Faus et al. 2009). These standards and potential regulations are under revision, since research is still ongoing on the mechanisms by which the chemicals applied to the fields can be transported to water bodies. For example, chemicals can be transported attached to sediment in a water stream. Crop residues (cellulosic material) protect the soil surface from the erosive effects of wind and rainfall, limiting the amount of sediment that leaves the field. Therefore, removal of these residues can have detrimental effects, increasing the final amount of chemicals reaching water bodies. In the following section, we will review the fertilizers and pesticide requirements of several crops considered for biofuel production, as well as summarize the findings of peer-reviewed studies on the effect of removal of agricultural residue and till practices on water quality.

A final issue that has not received deserved attention is that of the water and land resources demand for biofuels production. Forecasting future demand for such natural resources and comparing them to available resources is a difficult task due to the many sources of uncertainty surrounding those matters. Water and land requirements of biofuels will depend on what feedstock is used, as well as where the feedstock is grown. Additional temporal variability of climate plays a key role in forecasting the intensity of use of these resources, as well as its availability (think of droughts). Changes in agricultural irrigation techniques that might come through regulation or by choice, biotechnology advances, such as improvement of crop yields, and conversion technology changes can alter the final value of overall land and water requirements. The high number of variables suggest that the proper method for this analysis is through the generation of possible future case scenarios. Unfortunately, these issues have not been addressed by many scientists. In this report, we show what is probably the only scenario constructed to date: a baseline scenario using current statistics, current state-of-the-art technology, and current biofuel projections of the Energy Independence and Security Act (EISA) of 2007, as constructed by researchers at Rice University. Ongoing research at Rice is developing alternative scenarios, using an agricultural-climatic model combined with multiple potential technological, political, and climatic changes.

Current State of Knowledge

1. *Groundwater Pollution from Underground Storage Tanks*

The main points of this analysis are:

- Ethanol is easily degraded in the environment and has a relatively short half-life (time necessary for its concentration to be reduced to one-half of the original value) compared to other constituents of concern in gasoline, such as BTEX and MTBE;

- Human exposure to fuel ethanol is not expected to be significant due to its short life in the environment;
- Ethanol metabolism by ingestion into the human body and its related health effects indicate that environmental exposures to ethanol on humans have minimal adverse health impacts;
- Ethanol can directly hinder the biodegradation and natural attenuation of BTEX, leading to increases in plume lengths and a higher likelihood of BTEX reaching receptors;
- Ethanol can change the growth and distribution of microbes, stimulating the proliferation of microbial populations that degrade it, as well as BTEX degraders that fortuitously grow on ethanol. This response to changes in oxygen and substrate availability can offset, but not overcome, the mechanisms that hinder BTEX degradation activity at the individual cell level. These include catabolite repression, which is defined as the repression of inducible enzymes that degrade the target pollutant (e.g., BTEX) by the presence of a preferred carbon source (e.g., ethanol), and metabolic flux dilution, which is defined as a decrease in the specific BTEX utilization rate due to noncompetitive inhibition when ethanol is present;
- The rate and metabolic end products of ethanol degradation vary depending on the amount and concentration (E-10 vs. E-85) at the release site. This, in turn, determines the type of end products at a receptor site;
- The released ethanol-rich phase is lighter than water and may concentrate in the source zone at the water table interface. There, it would decrease the surface tension and facilitate spreading through the capillary zone. As ethanol becomes diluted, the cosolvent effect decreases and hydrocarbons come out of solution (phase-separation), creating a residual nonaqueous phase liquid (NAPL) lens at the water table interface that serves as a source of long-term groundwater contamination;
- Since ethanol is infinitely soluble in water, ethanol separates from the NAPL, dissolves and is carried with the groundwater and rapidly begins biodegradation. For most releases of E-10, ethanol rapidly biodegrades both aerobically (with oxygen) or anaerobically (without oxygen) near the release site, with most plumes migrating more slowly and

disappearing more rapidly than BTEX plumes (1 to 2 years);

- Complete aerobic biodegradation of ethanol produces CO_2 and water (acetaldehyde and acetic acid [vinegar] as intermediates). This process consumes the oxygen in the surface soils and potentially the subsurface aquifer. The more ethanol released, the more oxygen consumed;
- Anaerobic biodegradation of ethanol begins when oxygen has been depleted from the surface soils or when ethanol migrates into an oxygen-deprived zone in the subsurface. Anaerobic biodegradation depletes these regions of electron acceptors (sulfates, nitrates, iron, and manganese) and can lead to the accumulation of acetic acid, methane, and hydrogen gas; and
- Ethanol may also act as a cosolvent if present in groundwater at concentrations greater than 10,000 mg/L, increasing BTEX dissolution and mobility.

Direct health and environmental effects of ethanol releases in the environment are very unlikely to have strong adverse consequences. This is mainly due to the fact that: (1) fast degradation of ethanol, through aerobic and anaerobic processes, readily occurs in the environment (Ulrich 1999; Corseuil et al. 1998; Suflita and Mormile 1993); (2) due to its fast degradation and short life in the environment, exposure of humans to toxic ethanol levels is not expected (Armstrong 2000); (3) literature on ethanol metabolism by humans, and the related health effects of ethanol ingestion, indicate that environmental exposures to ethanol have a minimal adverse health impact, with no symptoms observed below 1000 ppm (American Conference of Governmental Industrial Hygienists [ACGIH] 1991; Clayton and Clayton 1994); (4) the human body metabolizes and eliminates ethanol very quickly (Pohorecky and Brick 1987; Holford 1987); and (5) ethanol is not persistent in the environment—it has a surface water half-life of 6.5 to 26 hours (Howard et al. 1991).

On the other hand, ethanol has the potential to affect the natural attenuation and transport processes of other target pollutants, like BTEX. The preferential biodegradation of ethanol and associated accelerated depletion of dissolved oxygen and nutrients in aquifers may hinder BTEX degradation. Decreased natural attenuation would, in turn, increase the length of BTEX plumes, which raises a concern for increased down-gradient exposure (Da Silva and Alvarez 2002; Ruiz-

Aguilar et al. 2002; Lovanh, Hun, and Alvarez 2002). A statistical study of benzene plumes resulting from regular versus E-10 (10 percent v/v ethanol/gasoline) gasoline spills shows an average 36 percent increase in benzene plume length when ethanol is blended with the gasoline. (Ruiz-Aguilar, O'Reilly, and Alvarez 2003). Laboratory experiments (Da Silva and Alvarez 2002; Lovanh, Hun, and Alvarez 2002; Lovanh and Alvarez 2004; Ruiz-Aguilar et al. 2002) and modeling studies (Heermann and Powers 1996; McNab, Heermann, and Dooher 1999; Molson, Barker, and Frind 2002; Gomez et al. 2008; Deeb et al. 2002) have also shown this elongation for benzene, with changes ranging from 10 percent to 150 percent. This is particularly important as benzene is potentially the most toxic of the BTEX hydrocarbons, and its presence in gasoline-contaminated sites often dictates the need for remediation.

Many unknown factors influencing benzene plume length elongation remain, such as the age and amount of spill, hydraulic conductivity, soil porosity, redox conditions, etc. As a result, there is still considerable uncertainty regarding the magnitude and importance of the BTEX plume elongating effects of ethanol. To address this uncertainty, a new mathematical model was recently developed to evaluate plume elongation mechanisms and their relative importance (Gomez et al. 2008), and to simulate plume elongation as a function of ethanol content in gasoline (Gomez and Alvarez 2009). This modeling effort concluded that plume elongation is primarily due to accelerated depletion of dissolved oxygen during ethanol degradation, and to a decrease in the specific rate of benzene utilization resulting from metabolic flux dilution and catabolite repression. Benzene plume lengths during the simulations showed elongations of ~60 percent for E-20 fuel ethanol blends and of ~34 percent for E-85 blends. Life span of the plume was also significantly shorter for blends with higher ethanol content: 17 years for regular gasoline, 15 years for E-10, nine years for E50 and three years for E-85. Increased microbial activity due to the presence of ethanol, as well as lower mass content of benzene on the blends due to dilution, account for the increased natural attenuation potential of higher ethanol blends.

<u>Effect on the Unsaturated Zone</u>

Ethanol can exert cosolvent effects that influence blended gasoline migration in the unsaturated zone. First, reduced surface and interfacial tension due to ethanol results in a more complete drainage of gasoline, leaving less residual chemicals entrapped in the unsaturated zone. Second, a significant fraction of ethanol partitions and is retained by residual water in the capillary zone. As this residual ethanol filters into the lower gasoline pool, it creates a nonuniform distribution of ethanol on the light nonaqueous phase liquids (LNAPL) pool. This heterogeneous LNAPL lens complicates the calculation and behavior of BTEX dissolution from the source. Finally, the infiltration rate of residual ethanol toward the capillary fringe and the gasoline pool is limited by the increased viscosity and, therefore, reduced unsaturated hydraulic conductivity of this phase (Powers and McDowell 2001c). Another important property of ethanol is that in high concentrations it partitions from fuel ethanol blends due to its higher buoyancy. This leads to a phase separation and accumulation of ethanol on the capillary fringe, resulting in lower groundwater concentrations near the source than would be expected if ethanol were considered completely miscible (Cápiro et al. 2007).

Enzyme Induction and Repression

Easily degraded substrates, like ethanol, are often preferentially degraded by microorganisms over more important target contaminants like benzene. One of the mechanisms for this is enzyme repression, where the presence of the preferred substrate inhibits the production of the enzyme required to degrade the target pollutant (Duetz et al. 1994; Monod 1949). This repression of benzene-degrading enzymes in the presence of ethanol was reported by Hunt et al. (1997a) during aerobic degradation experiments where benzene degradation was delayed. Furthermore, microcosm studies by Corseuil et al. (1998) indicate that this mechanism might lead to slower in situ BTEX biodegradation. This mechanism, known as catabolic repression, prevents microorganisms capable of degrading benzene from utilizing their full potential, hindering BTEX degradation and natural attenuation (Madigan, Martinko, and Parker 2005).

Other studies also point to carbon-limiting conditions as responsible for multi-substrate utilization (Egli 1995), where a decrease in the specific benzene utilization rate is due to the presence of ethanol, which is degraded simultaneously, a phenomenon also known as metabolic flux dilution (Lovanh and Alvarez 2004).

Stimulation of Microbial Growth

One of the advantages of ethanol is that it promotes the growth of a wide variety of microbial populations, including those that can degrade BTEX compounds (Alvarez 1999; Cápiro et al.

2008). Proliferation of BTEX degraders on ethanol (also known as fortuitous growth) would result in faster BTEX degradation rates. Unfortunately, this positive effect of ethanol is likely to be offset by its preferential degradation through the previously mentioned catabolic repression and metabolic flux dilution. Ethanol degrading enzymes are associated with central metabolic pathways, which can be utilized by many species that cannot degrade BTEX. Furthermore, favorable thermodynamics lead to faster microbial growth on ethanol than on BTEX compounds, with an increase in maximum specific growth rate of ~45 percent (Hunt 1999; McCarty 1969). The overall result of these processes is a significant increase in BTEX degrading microbial populations due to ethanol presence. However, ethanol can stimulate the growth of other bacteria faster than BTEX degraders, which decreases their relative abundance (Da Silva and Alvarez 2002; Cápiro et al. 2007), a phenomenon known as genotypic dilution.

<u>Microbial Toxicity of Ethanol</u>

Ethanol has been shown to have high concentration toxicity values. Several sources report an EC50 concentration (when microbial activity has been reduced by 50 percent of its maximum) between 31,000 mg/L and 57,000 mg/L (Dutka and Kwan 1981). Ethanol concentrations higher than 40,000 mg/L are toxic to most microorganisms, as shown during aerobic degradation experiments reported by Hunt et al. (1997a). Ethanol is toxic to microorganisms through disruption of the cellular permeability barrier (Brusseau 1993; Ingram and Buttke 1984; Harold 1970). In the presence of soil, microorganisms can find some protection, increasing effective toxicity values in the field. Microbial activity can occur at concentrations up to 100,000 mg/L (Araujo et al. 1998). The majority of microorganisms have toxicity values to ethanol in the range of 10,000 to 100,000 mg/L.

<u>Depletion of Nutrients and Electron Acceptors</u>

Compared to BTEX and other gasoline components, ethanol exerts a significantly higher biochemical oxygen demand in groundwater. This results in an accelerated consumption of dissolved oxygen within the ethanol plume (Corseuil et al. 1998). Fast oxygen depletion hinders aerobic BTEX degradation, and particularly of benzene, as it degrades at a much slower rate under anaerobic conditions (Alvarez and Vogel 1995; Anderson et al. 1998; Weiner and Lovley 1998a). Anaerobic degradation of BTEX is also affected. Ethanol can be anaerobically degraded under most common electron-acceptor conditions and this will lead to the depletion of other important dissolved electron acceptors (i.e., ferric iron). Field studies were conducted by Barker et al. (1992) using methanol, which presents environmental impacts similar to those of ethanol. These studies involved releasing controlled amounts of BTEX and methanol mixtures. The experiment showed, over the course of 476 days, that BTEX degradation is hindered by the presence of methanol in the gasoline plume.

Accumulation of Volatile Fatty Acids

Ethanol degradation by mixed anaerobic cultures can result in the production of volatile fatty acids (VFAs) (acetic, propionic, and butyric acid), which can accumulate and decrease the groundwater pH (Lasko et al. 1997; Speece 1983) and contribute undesirable taste and odor to the groundwater. This change in site conditions can also adversely affect some microbial populations that perform BTEX natural attenuation. Methanogens can be inhibited by pH lower than 6 (McCarty 1964), resulting in lower degradation rates of BTEX under such conditions. It is not known if VFAs would accumulate in the field to the levels required to significantly decrease the pH, inhibit microbial growth, and result in decreased natural attenuation rates. These effects are likely to vary locally and be specific to site characteristic. Another potential impact of this anaerobic souring effect is the reductive dissolution of metals that can further contribute to water quality degradation.

Impact of Microbial Processes on Aquifer Permeability

Microbial growth is highly stimulated by ethanol’s presence. This enhanced microbial growth could affect the hydrodynamic properties of the aquifer through the formation of biofilm and microbial cell aggregates that can reduce the available pore space and become a potential clogging mechanism (Taylor and Jaffe 1990; Vandevivere and Baveye 1992). Microorganisms could also affect aquifer permeability by increasing mineral dissolution (for example, $CaCO3$) and precipitation (for example, FeS). These opposing processes could affect soil pore space, affecting the available area for contaminant sorption, thus affecting hydraulic conductivity and darcy velocity, among other properties. However, laboratory column studies suggest that such effects are minimal (Da Silva and Alvarez 2002).

Sorption and Cosolvency

Ethanol can have two effects on BTEX concentrations due to cosolvency effects. First, the presence of ethanol in the water phase can decrease sorption-related retardation and is likely to increase BTEX plume lengths. The effect of a cosolvent on BTEX has been described by Rao et al. (1985). Cosolvent effects on sorption at ethanol concentrations expected from gasohol spills should be minor, as shown by Powers (2001) and model simulations (Gomez et al. 2008).

The second effect is how ethanol can change the equilibrium partitioning of BTEX compounds between the LNAPL phase and the water phase, which would have a direct impact on dissolution rates of BTEX from spills into the ground, and pore water and the resulting plume concentrations. Batch-equilibrium experiments were performed by Heermann and Powers (1998) and compared with three mathematical models. Results of these experiences show an overall increase in partition coefficients as a function of increasing ethanol content in the aqueous phase. Heermann and Powers developed a model to predict BTEX concentrations using a linear relationship for low ethanol volume fractions and a log-linear model for higher concentrations, which showed that changes in gasoline-water partition due to ethanol can be significant.

Overall, although ethanol itself does not present a significant risk associated with drinking water quality (other than perhaps to pregnant women if drunk in excess), its presence in contaminated groundwater is likely to hinder the natural attenuation of hydrocarbons and elongate benzene plumes, which represents a higher risk of cancer due to down-gradient exposure. Based on the statistical field studies of Ruiz-Aguilar, O'Reilly, and Alvarez (2003), and the previous laboratory and simulation studies (Da Silva and Alvarez 2002; Lovanh, Hun, and Alvarez 2002; Lovanh and Alvarez 2004; Ruiz-Aguilar et al. 2002; Heermann and Powers 1996; McNab, Heermann, and Dooher 1999; Molson, Barker, and Frind 2002; Gomez et al. 2008, Deeb et al. 2002) BTEX plume elongation is expected in the range of 35 percent to 55 percent when ethanol is present. For an average benzene plume of 200 ft, this would mean a length of 270–310 ft under the influence of ethanol. Values in this range have been shown in recent E-10 fuel simulation studies by Gomez et al. (2008). This is a significant increase of 70 to 80 ft over the regular gasoline baseline.

However, the magnitude and significance of the plume-elongating effect is likely to be site-specific, depending on the release scenario (e.g., how much was released and what type of blend) and the assimilative capacity of the aquifer (e.g., the rate of oxygen replenishment, which often controls the rate of benzene degradation). Thus, ethanol is unlikely to pose a serious threat to public health because drinking water wells are often miles down-gradient of gasoline stations and the elongating effect would be only on the order of 100 ft, which would be insufficient to reach well fields.

Based on all previous research and literature, we can arrive at the following conclusions:

- Following a release of E-10, the rapid diffusion and biodegradation of ethanol do not allow benzene to cosolvate with ethanol. Hence, cosolvency does not contribute to the extension of a benzene plume at low ethanol (E-10) concentrations. However, as the concentration of ethanol increases due to the release of higher concentrations of ethanol (E-85) or the inhibition of ethanol biodegradation (product inhibition*),* cosolvency may enhance the migration of the LNAPL and the dissolution of hydrocarbons, including benzene. Whereas benzene biodegrades in an aerobic environment, it is relatively recalcitrant under anaerobic conditions. The intense biodegradation of ethanol depletes the oxygen in its plume path, thereby inhibiting aerobic benzene biodegradation and contributing to extended benzene plumes. Benzene plume elongation is also encouraged by the preferential (diauxic) or concurrent biodegradation of ethanol, which decreases the rate of benzene degradation. Higher ethanol concentrations intensify these effects. It is clear that amounts of ethanol greater than 10 percent can significantly impact the degradation of benzene, thereby prolonging and extending the length of the benzene plume. In amounts 10 percent or less, there are varying reports as to whether ethanol will extend plume migration;
- Benzene can degrade anaerobically using the electron acceptors noted above for ethanol anaerobic biodegradation (sulfate, manganese (IV), iron (III), carbon dioxide). However, the depletion of electron acceptors by ethanol anaerobic biodegradation (methanogenic conditions) can remove electron receptors required for benzene anaerobic biodegradation, allowing this condition to persist even after ethanol has been completely degraded, thereby extending benzene plumes;
- Ethanol may stimulate microbial populations that enhance benzene biodegradation,

thereby offsetting the benzene plume elongation effect caused by preferential utilization of ethanol and the associated electron acceptor depletion.

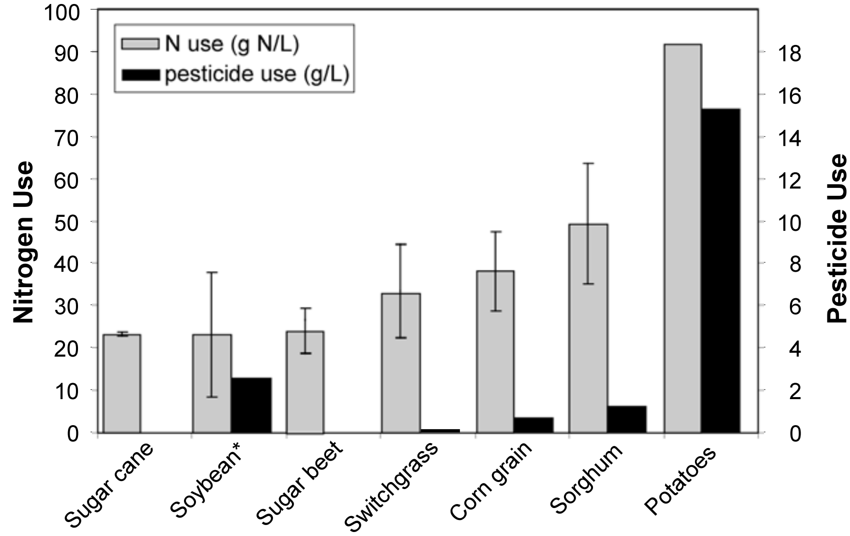
2. *Surface Water Quality from Agriculture of Energy Crops*

Chemical Uses and Agricultural Practices

To meet the mandated increased production of biofuels, increased agricultural activity such as tilling more acres and higher agrichemical application is inevitable, as are some adverse impacts that range from local groundwater degradation to eutrophication of distant coastal waters (Goolsby et al. 1999). Annual row crops, such as those typically used as biofuels feedstock, are especially prone to cause soil erosion and nutrient runoff to surface water, with corn having the highest nutrient application rate and water needs and highest nutrient loading to surface waters on a per land area basis. Marginal lands, which require even higher fertilizer application and are more susceptible to erosion and runoff, will also be pressed into agricultural service to meet the EISA mandate and take advantage of beneficial crop prices. This will create the potential for an exponential increase in detrimental impacts to water quality.

As shown above for water usage, agrichemical application rates vary widely among crops. Figure 1 presents the application rates for nitrogen fertilizer and pesticides available for bioenergy crops in a manner that normalizes the application rates to biofuel production potential.

Figure 1. Nitrogen and Pesticide Requirements for Producing One Liter of Ethanol from Different Crops.



*Note: Data are based on FRIS 2003 and National Agricultural Statistics Service (NASS) agricultural chemical usage datasets from the USDA. Data for pesticide application is not available for all crops. *Soybean is used for biodiesel production, and its requirements were estimated for an energy-equivalent volume of ethanol. See additional details in the Supplemental Information of Dominguez-Faus et al. 2009).*

Table 1. Pesticide Use Data

Crop	*Year of data*	*Harvested area (1000 ha)*	*Total U.S. Pesticide Use*				*Pesticide Application*	
			herbicide (ton)	*insecticide (ton)*	*fungicide (ton)*	*other (ton)*	*application (kg pest./ha)*	*g pest./ L etoh*
Corn	2005	30,947	71,625	2,204	42	0	2.39	0.66
Potatoes	2005	342	634	445	2,515	30,923	100.94	15.29
Soybeans	2005	26,237	35,085	1,086	87	0	1.38	2.57
Sorghum	2003	3,426	6,995	120	0	0	2.08	1.24
Switchgrass	--	--	--	--	--	--	3.00	0.08

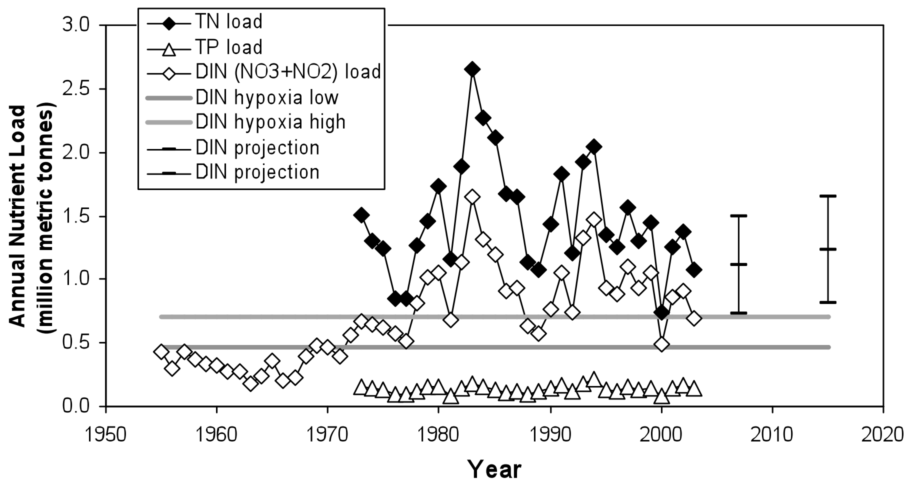
*** Assumed 3 kg/ha in first year, averaged over total 8-year harvest*

The pesticide data show the sum of herbicides, insecticides, and fungicides (Table 1). (The high value for potatoes is largely due to the use of sulfuric acid at harvest time to kill plant shoots to make the harvest easier.) Other common pesticides include atrazine and alachlor for corn and glycophosphate, used primarily on soybeans. The estimated pesticide application for switchgrass assumes 3 kg/ha of broadleaf herbicides (e.g., atrazine and 2,4-D) used in the first year only for switchgrass establishment. The impact of these agricultural pesticides on water quality continues to be studied and is often hotly debated. For example, in a 2003 study, atrazine was implicated as an endocrine disruptor contributing to mutations in frogs even at very low concentrations (Hayes et al. 2003).

From the perspective of the total nutrient use, the increase in agriculture to meet the mandated 15 billion gallons of fuel ethanol from corn by 2015 will require an expansion of agrichemical usage, including 2.17 million tons of additional nitrogen fertilizer, which is about 16 percent of the N fertilizer used for all crops in the United States (National Agricultural Statistics Service 2008). The high fertilizer application rates, especially for row crops in the midwestern United States, provide the greatest fluxes of nitrogen and phosphorus to local waterways and the Mississippi River basin (Powers 2007), and are considered one of the primary contributors to the growing hypoxic zone in the Gulf of Mexico, which covered over 20,000 km^2 in 2007 and is predicted to be bigger than ever in 2008. The discharge of nutrients from the Mississippi River to the Gulf of Mexico has been measured by the USGS for decades (Figure 2). The total nitrogen load is comprised primarily of dissolved inorganic nitrogen (DIN), with organic and particulate nitrogen forms contributing approximately 40 percent of the total nitrogen load.

The gray lines in Figure 2 define the estimated maximum DIN export required to achieve the federal goal for reducing the Gulf of Mexico hypoxic zone to < 5,000 km^2. The upper bound (0.7 million tons-N/y) is the federal Hypoxia Task Force recommendation of a 30 percent reduction in mean DIN load, and the lower bound (0.47 million tons-N/y) is the 55 percent reduction in mean DIN load thought necessary to account for variability in climate and ocean dynamics. Clearly, the current DIN loads (0.94 ± 0.26 million tons-N/y average over a 20-year period [1984–2003]) already greatly exceed these goals. Donner and Kucharik employed a rigorous agricultural and process-based dynamic ecosystem model to predict the impact of increased corn production in the Midwest on nitrogen export to the Gulf of Mexico (Donner 2003; Donner and Kucharik 2003; Donner, Kucharik, and Foley 2004; Donner and Kucharik 2008). The symbols included in Figure 2 for the year 2015 are their estimates for the mean (± 95 percent confidence interval) DIN exports that will result with expanded production to meet the 15 BGY corn-based ethanol goals. The results show that the anticipated increase in corn cultivation would increase the annual average load of DIN by 10–18 percent and increase the odds that these nitrogen loads will exceed the target set for reducing hypoxia in the Gulf of Mexico. Thus, expanding corn-based ethanol production would make it even more challenging to reverse the damage to this important ecosystem and fisheries area without significant changes in agricultural management (Goolsby et al. 2000).

Figure 2. **Annual Nutrient Loads at the Mississippi River St. Francis Sampling Point (USGS station number 07373420) Near the Mouth of the River (USGS 2008).**



Note: The grey bars represent the goal for the range of DIN loads necessary to reduce the size of the hypoxic zone to 5,000 km^2 (EPA 2008b).

Nutrient loads to the Gulf of Mexico are highly dependent on the annual rainfall in the upstream Midwest each year, total nutrient application, and land usage for crops. For corn and soybean row crops, the average nitrogen discharged from the fields to surface waters through runoff, sediment transport, tile drainage, and subsurface flow represents 24–36 percent of the nitrogen fertilizer applied, although this fraction can range from 5 to 80 percent in extreme years of drought (e.g., 1988, 2000, Figure 3) and flooding (1983, 1993) (Powers 2007). Land use and crop selection can greatly change the amount reaching surface waters. Nutrient discharges are greatest in the more humid corn and soybean regions across Illinois, Indiana, and Ohio (Goolsby et al. 2000; Donner, Kucharik, and Foley 2004; Burkart et al. 2006; Donner and Kucharik 2008). The presence of tile drainage in these areas of higher rainfall increases transport fluxes. A study comparing tile drained and nondrained soils in Iowa showed that the fraction of nitrogen fertilizer lost to surface waters ranged from an average of 8 percent in nondrained fields to 36 percent in tile drained fields (Powers, Ascough, and Nelson 2008). The eastern regions of the Corn Belt contribute less to the water consumption aspect of the water footprint, but they contribute more to the water pollution component of the overall water footprint.

Less information is available regarding nutrient losses from other potential biofuel crops, with switchgrass being the only other crop recently considered. The EPA Chesapeake Bay office

(Chesapeake Bay Commission 2007) modeled the potential changes in nutrient loads resulting from increased biofuel production in the watershed, and projected a substantial reduction in nitrogen loads to the Chesapeake Bay if cover crops are integrated into the soil (~7,800 metric tons N/y) or if farmland is converted to switchgrass with no fertilizer (~11,500 metric tons/y). In comparison, the Bay program partners are striving to reduce loads by 41,000 metric tons from all sources. Thus, some of these changes will contribute substantially to that goal.

The assumption that no fertilizer would be used on the switchgrass fields in the Chesapeake Bay region is inconsistent with other reports that recommend between zero and several hundred kilograms of nitrogen fertilizer per hectare, with an average of 32 kg N/ha in available field trials (see Supporting Information for Dominguez-Faus et al. 2009). These discrepancies exist because of the lack of data associated with switchgrass cultivated as a cash crop, the uncertain relationship between fertilizer application and increased yields, and the lack of field measurements quantifying the fate of the fertilizer in the soil, air, and water after application. Switchgrass uses applied N efficiently (Parrish and Fike 2005), and it appears able to obtain N from sources that other crops cannot tap. As a result, the N removed in harvested biomass can be greater than the amount of N applied. The long-term impacts on soil productivity are as yet unknown. In areas with sufficient rainfall, annual sustainable switchgrass yields of 15 metric tons/ha may be achievable by applying 50 kg N/ha (Parrish and Fike 2005). Other estimates suggest that 90 kg N/ha would be required for switchgrass and that the fraction of the fertilizer that was lost to surface water (30 percent) would be similar to corn (Miller, Landis et al. 2007). With a harvest yield of 10 metric tons/ha, this would result in a loss to surface water of 12 kg N/metric ton. The modeling study by Powers et al. assumed a much higher average fertilization rate for switchgrass grown in Iowa (0 kg/ha in year 1 to 260 kg/ha in years 6–8), and predicted that the average total nitrogen loads to surface water would be 7.8 kg N/ha, representing 4.2 percent of the nitrogen fertilizer applied (Powers, Ascough, and Nelson 2008).

It is better to compare among the feedstock on the basis of fuel energy generated. Table 2 shows model predictions for a variety of crops with both conventional tillage (CT) and no-till (NT) management practices. For the corn-soybean (CS) rotations, the no-till option reduces nutrient (40 percent) and soil loss (75 percent) relative to conventional till and the change to harvesting

50 percent of stover residue or a change in the crop to switchgrass reduces nutrient and soil loss by a factor of 5–10 on an energy normalization basis.

Table 2. Modeled Nutrient Losses and Soil Erosion for Energy Crop Scenarios when Normalized by Energy Content

Summary	*g/MJ fuel TN/energy*	*g/MJ fuel TP/energy*	*t/MJ fuel soil/energy*
Corn (CSCT)	0.37	0.050	0.109
Corn (CSNT)	0.27	0.034	0.028
Soy (CSCT)	2.28	0.308	0.671
Soy (CSNT)	1.55	0.192	0.159
Stover 50% (CSNT)	0.028	0.004	0.010
SG	0.065	0.037	0.016

Source: Powers, Ascough, and Nelson 2008

Notes: All values averaged over 26-year period with soils and climate typical of eastern Iowa; CSCT/CSNT–corn soybean rotation with conventional till/no till; Stover–harvest of 50 percent of available stover as part of CSNT rotation. Model assumes that no extra fertilizer is applied to replace the nutrient content of the harvested stover; SG–switchgrass with increasing fertilizer rates over the crop life. Model includes two consecutive 8-year cycles.

<u>Land Use Changes that Could Impact Water Quality</u>

Prior to the current ethanol mandate and subsidies, fuel crops were generally grown where it was most economically and environmentally sound to do so. This was in part due to the conservation reserve program (CRP), which pays farmers not to utilize highly erodible and minimally productive lands. CRP contracts are ranked and selected based on the Environmental Benefits Index (EBI) to target retiring land from row crop production, which causes the greatest detriment in terms of erosion, runoff, and leaching of nutrients. In 2007, over 14 million hectares were enrolled in the CRP, producing notable reductions in pollutant loads to surface water, including reductions of 187 million metric tons of sediment erosion, 218,000 metric tons of nitrogen and 23,000 metric tons of phosphorous (National Agricultural Statistics Service 2008). The program was also reported to sequester an estimated 45 million metric tons of carbon per year. CRP lands are often planted with switchgrass or short rotation woody perennials including willow and poplar that can also serve as biofuel crops. This selective planting clearly shows benefits of these crops on surface water quality, the overarching goal of the CRP.

Re-enrollment of lands in the CRP is dropping however, and participants are requesting early release from CRP contracts in order to take advantage of subsidies and rapidly rising biofuels crop prices. In 2007, Secchi and Babcock estimated that over 526 thousand hectares of Iowa farmland would likely be pulled from the CRP and put into a corn/soybeans rotation if corn prices hit $196 per metric ton ($5 bushel) (Secchi and Babcock 2007). In June 2008, corn rose to nearly $314 per metric ton ($8/bushel), beyond the range modeled only one year earlier. Although CRP contracts are established on a 10 to 15 year basis, enrollment in the program is already decreasing. CRP enrollment dropped by more than 840,000 hectares in 2008. Due to the erodible and less-productive nature of most land enrolled in the CRP, removing land from the program for row crop production will likely lead to a nonlinear increase in erosion and nutrient loading to surface waters. One proposal to avert removal of land from the CRP program is to increase CRP payments, which totaled more than $1.6 billion in 2007 (National Agricultural Statistics Service 2008). However, some analysts suggest that even doubling the payments would not be sufficient to retain land in the CRP (Secchi and Babcock 2007).

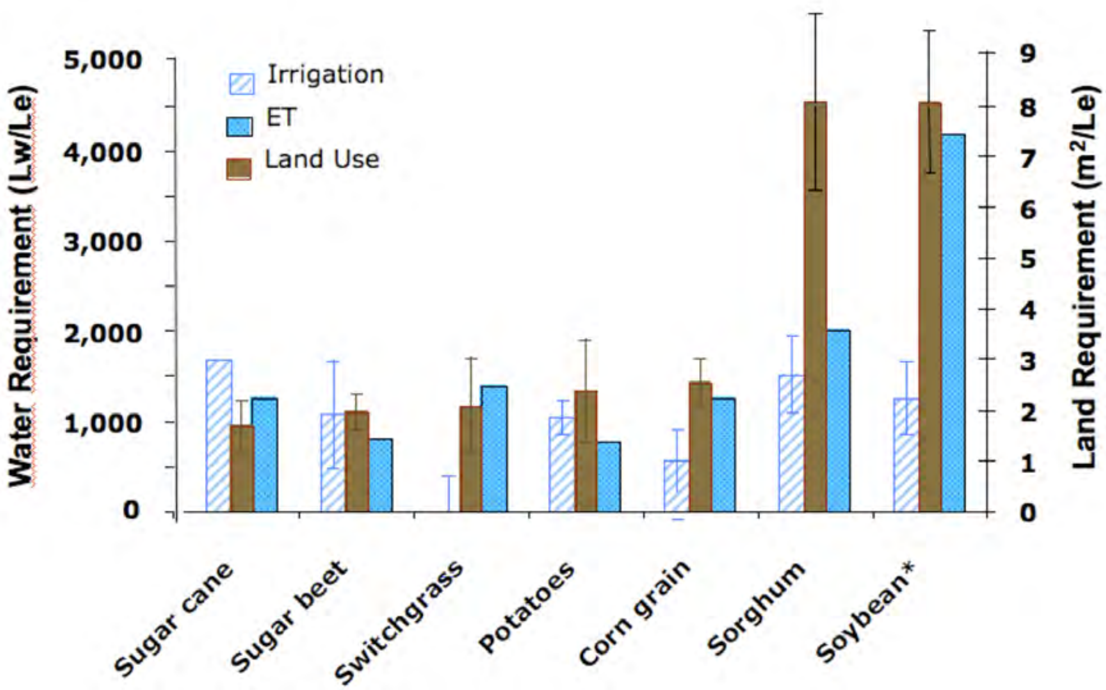
3. *Water and Land Requirements to Grow Energy Crops*

Water and Land Demands of Biofuels from Selected Traditional Crops and Switchgrass

The water requirements of biofuel production depend on the type of feedstock used and on geographic and climatic variables. Such factors must be considered to determine water requirements and identify critical scenarios and mitigation strategies. Feedstock cultivation, usually row-crop agriculture, is the most water-intensive of biofuels production stages. For example, processing water requirements for a typical sugarcane or corn-based ethanol refinery are around 2 to 10 liters of water per liter of ethanol produced (National Research Council 2008) while evapotranspiration water requirements to produce enough feedstock to make one liter of ethanol in the United States range from 500 to 5,000 liters (Figure 3). The water used in biofuel processing and other stages in biofuel production is often withdrawn from local point sources and can have localized impacts on water quality and quantity, despite their much lower overall water requirements.

Assuming a conservative volumetric water to ethanol ratio of 800 (e.g., for irrigated corn-based ethanol from Nebraska), and that a car can drive 16 miles on one gallon of ethanol (or 2/3 of the mileage from gasoline), this represents about 50 gallons of water per mile driven (gwpm). To illustrate the variability of the water requirement as a function of the crop used and where it is grown, this value could decrease to 23 gwpm for corn grown in Iowa, or increase to 90 gwpm if sorghum ethanol from Nebraska is used, or 115 gwpm if the sorghum is grown in Texas.

Figure 3. Water and Land Requirements in the United States for Ethanol Produced from Different Crops.



Note: White symbols represent irrigation requirements (weighted average one standard deviation for top producing States, from USDA and other pertinent statistics as described in the Supplemental Information section of Dominguez-Faus et al. 2009). Filled symbols represent evapotranspiration requirements (Chapagain and Hoekstra 2004). Note that soybean is used for biodiesel production, and its water and land requirements were estimated for an energy-equivalent volume of ethanol.

To minimize the water footprint of biofuels, it is important to recognize that some crops yield more biofuel energy with lower requirements for agricultural land, fertilizer, and water, and that consumptive water (evapotranspiration) requirements tend to increase with land requirement (Figure 3). Thus, from a water supply perspective, the ideal fuel crops would be drought-tolerant, high biomass plants grown on little irrigation water. Lignocellulosic agricultural residues or forest thinning removed without damaging soil properties would also be preferred feedstock from a water-use perspective. Currently, evapotranspiration requirements for fuel crops range in the United States from about 777 L of water per L ethanol produced (Lw/Le) for potatoes to 4,185 Lw/Le for soybean (Chapagain and Hoekstra 2004).

Water Uses in Other Energy Production Processes

To put these numbers in perspective, large quantities of water are also needed to produce energy from traditional sources (e.g., to pump petroleum out of the ground, generate steam to turn turbines, or cool nuclear power plants). However, the water requirements to produce an equivalent amount of energy from biofuels are comparatively large (Table 3).

Table 3. Water Requirements for Energy Production by Different Processes

Process	***L/MWh***
Petroleum extraction	10–40
Oil refining	80–150
NGCC* power plant, closed loop cooling	230–30,300
Coal integrated gasification combined-cycle	~900
Nuclear power plant, closed loop cooling	~950
Geothermal power plant, closed loop tower	1,900–4,200
Enhanced oil recovery	~7,600
NGCC*, open loop cooling	28,400–75,700
Nuclear power plant, open loop cooling	94,600–227,100
Corn-based ethanol irrigation	2,270,000–8,670,000
Soybean biodiesel irrigation	13,900,000–27,900,000

*Natural gas combined cycle

Source: Sandia National Laboratories, 2006

Figure 3 shows that both corn grain, which is the most common fuel ethanol crop in the United States, and switchgrass, which is a lignocellulosic crop, compare favorably to other fuel crops regarding both water and land requirements. In fact, the theoretical irrigation water requirement for prairie-grown switchgrass is zero. Nevertheless, despite intensive research activity on plant genomics and metabolic engineering to facilitate conversion of lignocellulosic feedstock into biofuels, current technology is not yet economically feasible to meet our large biofuel requirements from such feedstocks (Energy Forum 2008). Consequently, an initial reliance on corn-based ethanol appears unavoidable to reach the current EISA mandate.

Scaling-up Production

Meeting the mandated 57 billion liters (15 billion gallons) of fuel ethanol from corn by 2015 will use 44 percent of the 2007 U.S. corn production. If all corn were planted in irrigated land, where corn yields are higher, it would require about 13.8 million hectares of irrigated land and consume 31.1 billion m^3 of irrigation water (Dominguez-Faus et al. 2009). If all the corn was to be grown on nonirrigated land, the water requirement would be nil, but the land requirement would be greater since corn yields would be lower. If the current proportion of irrigated corn (20 percent) was maintained throughout the expansion, it would require 29.3 million hectares of irrigated land and 6.3 billion m^3 of irrigation water, plus 117.2 million hectares of nonirrigated land.

Table 4. What It Will Take to Make Enough Corn-based Ethanol to Meet the EISA Mandate

Metric	***Quantity***	***Benchmark for Comparison***
Fuel Requirement	57 billion liters ethanol per year (15 billion gallons per year)	Energy-equivalent of 7% of 2006 annual gasoline consumption
Amount of feedstock	146.5 million metric tons (5.7 billion bushels)	44% of the 2007 U.S. corn production
Irrigated Land*	13.8 million ha (34.1 million acres)	8% U.S cropland
Irrigation Water*	31.1 billion m^3 (7.8 trillion gallons)	16.5% of current irrigation water use in the United States or 5% of the 92-year average annual discharge of the Mississippi River to the Gulf of Mexico
Total Land**	19 million ha (47 million acres) (16.2 million ha nonirrigated + 2.7 million ha irrigated)	11% U.S. agricultural land
Irrigation Water**	6.3 billion m^3 (1.6 trillion gallons)	3.23% of 2000 irrigation water use in the United States. (Compare to 1.23 trillion gallons withdrawn per year in Iowa for all uses.)

**Assuming all corn grown on irrigated land.*

*** Assuming only 20 percent of corn is irrigated (current situation).*

This scenario is built based on current harvest yield data and current ethanol yield efficiencies based on the biochemical transformation pathway of starches to ethanol. Improved corn and ethanol yields brought about by biotechnology advances, or consideration of other conversion pathways, such as thermochemical, could change these figures.

Geography Matters

Expansion of corn acreage will have different consequences depending on where it occurs. Rainfall can satisfy most of the agricultural water requirements for biofuel production in some regions (e.g., Ohio, where less than 1 percent of corn grown is irrigated), other regions rely primarily on irrigation (e.g., Nebraska, where 72 percent of corn grown is irrigated). This spatial variability makes it difficult to assess the potential for increased irrigation requirements to exacerbate competition for water resources and create local water shortages.

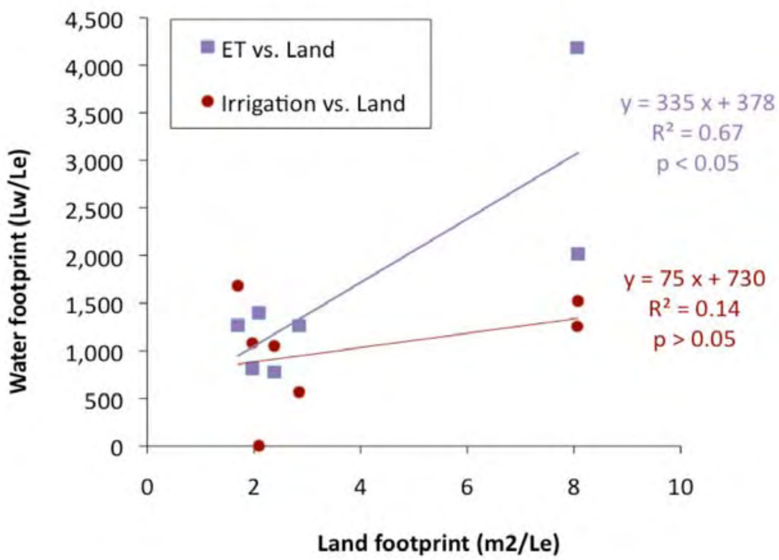
In already water-constrained areas, the choice of biofuel crops could lead to significant long-term impacts. With Texas experiencing the driest spring on record in 2003 and with western states from the Rockies to the Pacific Coast experiencing moderate to extreme droughts (Karl et al. 2008), most biofuel feedstock expansion is occurring in the Midwest where irrigated agriculture is increasing (National Agricultural Statistics Service 2008). According to the Intergovernmental Panel on Climate Change (IPCC) report (Kundzewicz et al. 2008) the East will get wetter and the West will get drier. Although the East is getting wetter, precipitation is less frequent and more intensive (Kundzewicz et al. 2008). Irrigation is necessary to provide water regularly to plants. In Nebraska, irrigated corn area surpassed all time highs in 2007 and 2008, with over 3.64 million hectares planted. The area is also already in all time water deficits and legal actions have been taken by Kansas, based on allegations that Nebraska farmers used 98 billion liters more than their allotment of the Republican River in 2004 and 2005, as ruled by the U.S. Supreme Court in 2003. Meeting the Kansas demand would mean shutting off irrigation to an estimated 485,000 hectares of Nebraska farmland. The Ogallala Aquifer is also being drawn down at record rates (U.S. Water News Online 2009). These rates are expected to increase considerably to meet irrigation and ethanol process water needs.

The estimates of overall water demand of scaled-up biofuel production shown in the previous section assume expansion will happen in ideal land conditions (like those of the Corn Belt). If expansion occurs in other not-so-suitable areas, water and land demand will be higher.

Components of Water Use

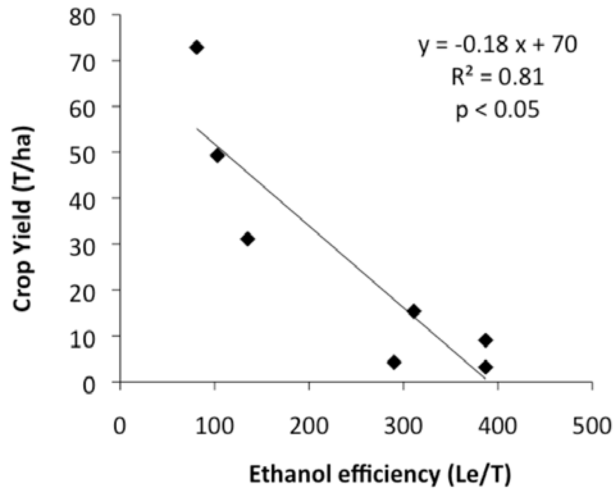
For the feedstock analyzed in this report, a correlation can be observed between consumptive water and land requirements to produce a liter of ethanol (Figure 4). So it can be said that a biofuel that is good for land conservation will be good for water conservation as well.

Figure 4: Correlation Between Water, both Consumptive (ET) and Withdrawals (irrigation), and Land Footprint.



However, high yield crops (tons of feedstock per hectare) do not necessarily have lower footprints than lower yield crops. This is because another conversion factor needs to be considered: ethanol conversion efficiency from the feedstock. Feedstock with both high crop yield and high ethanol conversion efficiency will have a low impact on both land and water resources. Unfortunately, crop yield and ethanol conversion efficiency are inversely correlated (Figure 5).

Figure 5. Correlation Between Crop Yield and Ethanol Conversion Efficiency



Ethanol yield efficiency is related to the glucose content of the feedstock, which depends on the type of sugar molecule and its concentration in the feedstock. Cellulosic and starchy crops contain a high percentage of complex sugar molecules, yielding more sugar molecules than sugarcane and sugar beets that can be converted to ethanol (Table 5).

Table 5. Sugar Content and Ethanol Yields of Sugar and Starchy Feedstock

Feedstock	***Starch content***	***Ethanol yields (L/Ton)***
Corn	70–72%	371
Sorghum	68–70%	371
Feedstock	***Sucrose content***	***Ethanol yields (L/Ton)***
Sugarcane	10–15%	73
Sugar beets	Slightly more than sugarcane	93

Source: USDA 2006

As a result, most feedstock have similar land and water footprint, because those with high crop yield have low sucrose content, and those with lower crop yield have higher sucrose content. This becomes very relevant when considering cellulosic feedstock because cellulose is a complex sugar molecule with high sugar content, and because the whole plant biomass, rather than the reproductive part (grain), only can be converted to ethanol, which is equivalent to having high crop yields.

Uncertainty of Climate

Extreme hydrologic events (droughts or floods) can impact feedstock production and availability. The 2008 floods and heavy rains in the Midwest washed away about 2 percent of the nation's corn crop, affecting mainly Iowa's production (National Agricultural Statistics Service 2008). The net effect on corn and soybean yields is yet to be determined. During 1993 flooding in the same region, corn and soybean yields in eastern Iowa counties were reduced to 61 percent and 74 percent of the average values during the 1990s (National Agricultural Statistics Service 2006).

Extreme hydrological events are likely to persist according to the U.S. Climate Change Science Program (Karl, Meehl et al. 2008), which infers that droughts will be more likely and severe in the Southwest, reducing regional water supply and increasing wildfire risks. Furthermore, cold season storms and floods will be more frequent in wet areas. On average, precipitation is likely to be less frequent but more intense, while heat waves are likely to increase and, consequently, more irrigation water would be necessary. Thus, in addition to geographical variability, temporal variability in water availability and in crop requirements confound our ability to determine the potential for biofuel irrigation to exacerbate competition for water resources and contribute to water shortages.

Water Use Projections for Other Sectors

Energy and agriculture already rank as the top two sectors in U.S. water withdrawals, accounting respectively for 48 percent and 34 percent of the total (Hutson et al. 2004). Regardless of climate change, the competition for water between these two sectors will intensify in the near future. The Energy Information Administration (EIA) predicts that thermoelectric generation from coal, natural gas, nuclear and other fuels will increase by 22 percent between 2005 and 2030 (Donner and Kucharik 2008), for example. Combined with a biofuel-induced increase in agricultural water use of 16.5 percent by 2015 (Table 4), the potential to create water shortages and conflicts cannot be dismissed.

4. *Greenhouse Gases and Air Quality Effects Associated with Biofuels Production and Use.*

Air quality is regulated by the Clean Air Act (CAA), which was last amended in 1990 although some minor changes have occurred since then. The CAA requires the U.S. EPA to set National Ambient Air Quality Standards (NAAQs) for six common air pollutants: carbon monoxide (CO), nitrogen oxides (NOx), sulfur dioxide (SO_2), lead (Pb), ozone (O_3), and particulate matter (PM). These six pollutants are known as "criteria pollutants" since the permissible levels of pollution are based on health and/or environmental criteria. Other gaseous emissions of environmental concern are those called greenhouse gas (GHG) emissions since it is believed that there has been an unprecedented accumulation of these gases in the atmosphere since the industrialization, and that they are causing anthropogenically-driven global warming. Carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are among the most prominent GHGs affected by biofuel production.

<u>Air Pollutants of Concern</u>

Not only are GHGs important when considering air quality implications of biofuels, but there are other air pollutants of concern.

Criteria Pollutants

Criteria pollutants are six common pollutants regulated by EPA based on human and environmental health guidelines. Such regulated pollutants are:

<u>Carbon Monoxide (CO)</u>

CO reduces oxygen delivery to human organs and tissues and is associated with heart problems; it induces vision problems and in extremely high levels can cause death. CO emissions are mainly produced during incomplete combustion of fuels. Biofuel blends, ethanol-gasoline or diesel-biodiesel result in decreasing rates of CO emissions, because the oxygen content of the biofuels allows for better fuel combustion. Values ranging from 10 to 30 percent smaller can be found (Pikunas, Pukalskas, and Grabys 2003; Yuksel and Yuksel 2004), with an ethanol-gasoline blend. For diesel-biodiesel, such values can reach 50 percent, depending on the amount of biodiesel in the mixture (Lapuerta, Armas, and Rodriguez-

Fernandez 2008). Although tailpipe CO emissions are smaller when using E-10 or E-85, life cycle emissions from E-85 are substantially higher than E-0 (Winebrake, He, and Wang 2000). Compared with conventional diesel, life cycle emissions for biodiesel can be considered smaller (Hill et al. 2006).

Nitrogen Oxides (NOx)

The two most important nitrogen oxide pollutants are nitric oxide (NO) and nitrogen dioxide (NO_2). These pollutants are emitted when fossil fuels are burned. In 2003, transportation accounted for 57 percent of emissions whereas stationary fuel combustion sources were responsible for 37 percent. Of the anthropogenic emissions of NOx, 95 percent are in the form of NO, which has no known adverse health effects at concentrations found in the atmosphere. However NO readily oxidizes to NO_2, which can irritate lungs, causes bronchitis and pneumonia, as well as lower resistance to respiratory problems. NO_2 can also react with OH in the atmosphere to form nitric acid (HNO_3), contributing to the acid rain problem.

NOx are also key precursor to another criteria pollutant: ground-level ozone (O_3). Results on literature regarding biofuel impacts on NOx are diverse. While some suggest tailpipe emission reduction ranging from 30 to 45 percent, when using E-85 (Jacobson 2007). Others suggest no changes (Graham, Belisle, and Baas 2008) or increases ranging from 6 percent (Cooney 2007) to 50 percent (Kim and Dale 2004). Biodiesel blends are responsible for linear increases in NOx emissions as the content of biodiesel in the mixture increases with reductions of about 12 percent for pure biodiesel (Lapuerta et al. 2008). Life cycle analysis (LCA) for NOx emissions, compared with base fuels, can be considered higher for both ethanol (6–7 percent) and diesel (12 percent).

There is a trade-off between reduction in emissions of carbon monoxide and nitrogen oxides. At higher combustion temperatures, however, there is a reduction in emissions of CO while emissions of NOx increase.

Particulate Matter (PM)

Particle pollution is made up of a number of components, including acids (such as nitrates and sulfates), organic chemicals, metals, and liquid droplets, soil, or dust particles. The size of particles is directly linked to their potential for causing health problems. EPA is concerned about particles that are 10 micrometers in diameter or smaller because those are the particles that generally pass through the throat and nose and enter the lungs.[38] These can aggravate respiratory and heart problems, cause nonfatal heart attack, and are also associated with premature deaths.

PM can be emitted directly as particles from incomplete fuel combustion or it can be formed in the atmosphere, when gaseous SO_2 and NOx are transformed into liquid droplets of sulfates or nitrates. As with CO emissions, the oxygen content of biofuels allow for a more complete combustion of such fuel, resulting in lower tailpipe emissions of PM. However, PM matter associated with wind erosion can result in higher LCA emissions for biofuels. In Brazil the pre-harvest burning of sugarcane significantly increases the amount of PM (Figure 2).

Figure 6. Pre-harvest Burning of Sugarcane in Brazil

[38] For more information, visit http://www.epa.gov/oar/particlepollution/.

Sulfur Oxides (SOx)

SO_2 causes a wide variety of health and environmental impacts because of the way it reacts with other substances in the air. Particularly sensitive groups include people with asthma who are active outdoors, children, the elderly, and people with heart or lung disease (Environmental Protection Agency 2009).

SOx are not a concern in terms of tailpipe emissions from motor vehicles. About 80 percent of the anthropogenic SOx emissions are the result of fossil fuel combustion in stationary sources, mostly coal-fired power plants. The only significant noncombustion sources of sulfur emissions are associated with petroleum refining, copper smelting, and cement manufacture. SOx emissions are associated with biofuels by the use of energy (electricity) either for irrigation or distillery energy supply. It is also associated with natural gas used in ethanol milling plants. Literature does not devote much attention for SOx LCA emissions. Overall results are still not clear, although the literature considers increases of SOx in LCA balances.

Ozone (O_3) – Tropospheric

Ozone is related to respiratory problems such as coughing, throat irritation, bronchitis, emphysema, and asthma. Tropospheric ozone is commonly formed in the presence of sunlight with NOx and volatile organic compounds (VOC). Since both increase with the use of biofuels, the tendency is for ozone to increase as well. An interesting study of possible consequences of E-85 use concluded that it "may increase ozone-related mortality, hospitalization, and asthma by about 9% in Los Angeles and 4% in the United States as a whole relative to 100% gasoline" (Jacobson 2007).

Volatile Organic Compounds (VOC)

VOC causes damage to the central nervous system and can cause cancer in humans and animals. Fatigue, nausea, and headaches are also symptoms associated with VOC exposure. This class of compounds consists of volatile compounds that enter the atmosphere when solvents, fuels, and other organics evaporate. The transportation sector is responsible for almost half of anthropogenic VOC emissions. This review focuses on five VOC compounds:

benzene, toluene, xylene, formaldehydes, and acetaldehydes. Adding ethanol to gasoline causes the mixture to increase its vapor pressure, resulting in increases of evaporative emissions. Tailpipe emissions of benzene, toluene, and xylene are reduced while acetaldehyde and formaldehyde emissions become significantly higher.

- Formaldehydes: 60 to 70 percent ↑
- Acetaldehydes: 100 to 2,540 percent ↑
- As for biodiesel, studies suggest a reduction of tailpipe emissions varying from 18 to 63 percent depending on the proportion of biodiesel in the mixture.

Total Hydrocarbons (THC)

THC emissions result when fuel molecules in the engine do not burn or burn only partially. HC react in the presence of nitrogen oxides and sunlight to form ground-level ozone. Usually THC, like CO and PM, is reduced in tailpipe emissions when biofuels are used due to better combustion as a result of the oxygen content of biofuels.

Table 6. Summary of Literature Review of Biofuel Use Compared with Base Fuels

Pollutant	Ethanol tailpipe	LCA Ethanol	Biodiesel tailpipe	Biodiese l LCA
NOx	↑ 6–40% ↓ 30–45%	↑	↑ 12%	↑
SOx	-	↑	-↓	↓
PM	↓	↑	↓ 18–71%	↑
CO	↓ 10–30%	↑ 7%	↓ 50%	↑
Ozone	-	↑	-	↑
VOC	↑ 2,000%	↑ 63%	↓ 18–63%	↑
THC	↓ 10–90%	↑	↓20–76%	↑

In summary, results of studies concerning air pollutants and biofuels use and production, as with the previous example of GHG emissions, can vary significantly. A few trends might be observed, however, such as the reductions in tailpipe emissions of CO, THC, and PM in vehicles using ethanol. Yet in order to have more accurate estimates of such emissions, more measurement experiments should be performed. That is true not only for tailpipe emissions, but as in the case of PM, for agriculture field emissions as well.

Research Needs

Geographical Distribution of Criteria Pollutants

Impacts on air pollution resulting from the use of biofuels tend to vary locally due to a series of factors. For instance, NOx emissions are associated with vehicle tailpipes while PM can be also important in agricultural areas due to wind erosion. SOx emissions, on the other hand, are associated with electricity consumed during different phases of biofuel production. Besides such aspects, local atmospheric conditions have an important role on the concentration of certain pollutants. Local atmospheric conditions not only affect air movement patterns, but they also impact local assimilation capacity and the complex interactions among pollutants in the atmosphere.

To maximize the benefits of biofuels and, in some ways, dilute their environmental impact, careful consideration should be given to the location of agricultural fields and biofuel plants, as well as the cities that primarily consume the fuels.

Professor Daniel Cohan's research group at Rice University has begun to address these issues by conducting air quality modeling for alternate scenarios of biodiesel deployment in the Houston region. Devoting the nation's entire soybean crop to biodiesel production would displace only 6 percent of total diesel use (Hill et al. 2006), and other feedstock face limited availability as well (Hanna, Isom, and Campbell 2005). Targeting biodiesel toward applications with maximal environmental benefit is thus crucial to optimizing its potential impact, especially if biodiesel is to be deployed in a pure form.

Despite the dozens of studies comparing the emissions from biodiesel and diesel on a tailpipe or life cycle basis, no published studies have yet examined how deployment and use of biodiesel could be targeted to optimize its air quality and health impacts. For example, for a given amount of biodiesel, what would be the relative impacts of deploying it broadly in low percentage blends versus targeting its use in higher blends to specific parts of the diesel fleet? Densely populated areas may stand to gain the most from biodiesel's propensity to reduce PM, CO, hydrocarbons, and air toxics, all of which have limited atmospheric lifetimes and directly harm human health (Brunekreef and Holgate 2002).

Human and Environmental Health Assessment

Additionally, to better assess GHG and pollutant emissions, it would be recommended that at some point this data could be used to evaluate the impacts on human health of such emissions. This can be accomplished by the use of the risk-assessment approach. Such an approach can also be useful to assess environmental impacts, some of which are discussed in other sections of this document.

Land Use Change – CO_2, CH_4, N_2O Emissions

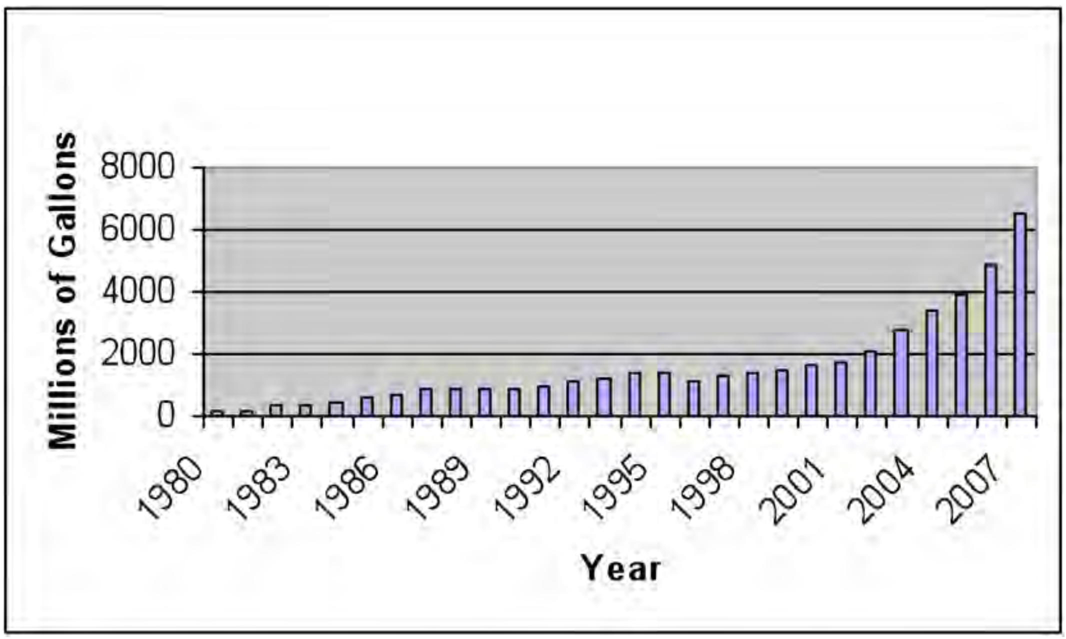
If biofuel production continues to receive incentives, it is very likely that land area devoted to biofuel crops will increase. This report noted earlier that this could lead to increased carbon emissions. Existing projections for future land use devoted to biofuel crops can be useful to estimate the net increase or decrease of CO_2, CH_4, and N_2O emissions by comparing this land use with current land uses. N_2O emissions could also be used to calculate how land use changes ultimately affect stratospheric O_3 emissions.

Appendix II[39]

Table 1. Historic U.S. Fuel Ethanol Statistics

Year	January 1999	January 2000	January 2001	January 2002	January 2003	January 2004	January 2005	January 2006	January 2007
Total Ethanol Plants	50	54	56	61	68	72	81	95	110
Ethanol Production Capacity	1701.7 mgy	1748.7 mgy	1921.9 mgy	2347.3 mgy	2706.8 mgy	3100.8 mgy	3643.7 mgy	4336.4 mgy	5493.4 mgy
Plants Under Construction/ Expanding	5	6	5	13	11	15	16	31	76
Capacity Under Construction/Expanding	77 mgy	91.5 mgy	64.7 mgy	390.7 mgy	483 mgy	598 mgy	754 mgy	1778 mgy	5635.5 mgy
Farmer Owned Plants	14	18	21	25	28	33	40	46	46
Farmer Owned Capacity	293.3 mgy	340.3 mgy	473 mgy	645.6 mgy	796.6 mgy	1041.1 mgy	1388.6 mgy	1677.1 mgy	1677.1 Mgy
% of Total Cap Farmer	17%	19%	25%	28%	29%	34%	38%	39%	39%
Farmer Owned UC Plants/Expanding	5	3	3	10	8	12	10	4	4
Farmer Owned UC Capacity	77 mgy	60 mgy	60 mgy	335 mgy	318 mgy	447	450 mgy	187 mgy	187 mgy
% of Total UC Capacity	100%	66%	71%	86%	66%	75%	60%	11%	11%
States with Ethanol Plants	17	17	18	19	20	19	18	20	21

Table 2. Historic U.S. Fuel Ethanol Production



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