Life Cycle Analysis of Greenhouse Gas Emissions Associated with Starch-Based Ethanol

PREPARED FOR:

THE AMERICAN COALITION FOR ETHANOL

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GLOBALINSIGHT

December 1, 2008

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Executive Summary

This study reviews the proposed approaches to life cycle analysis (LCA) for the purpose of determining greenhouse gas (GHG) emissions associated with biofuels as discussed by California and the U.S. Environmental Protection Agency (EPA). As discussed below, the overriding factor in the LCA approaches is the potential inclusion and methods used to calculate GHG emissions associated with indirect land use. Early estimates of GHG emission associated with indirect land use by some groups suggest these potential effects dwarf direct GHG emission reductions. If these methods are used, not only would starch-based ethanol lose its status as a renewable fuel, it would be labeled as a contributor to GHG emissions. As developed in the study, there are considerable difficulties with estimating the extent (if any) to which the biofuels industry contributes to indirect land-use change.

Background

In an effort to reduce emissions of GHG, California has proposed implementing a low carbon fuel standard (LCFS), which is a market-based approach to reducing vehicle emissions. The U.S. Congress also is expected to consider legislation that would feature an LCFS. This policy, whether implemented only in California or across the nation, would have major implications for all forms of motor fuels, including renewable fuels such as corn-based ethanol.

A key to implementation of an LCFS is an LCA of the GHG emissions of various types of fuel. An LCA is an attempt to quantify all of the emissions associated with the production, distribution, and consumption of a fuel. In the case of corn-based ethanol, the LCA considers GHG emissions associated with a wide variety of sources, such as

- the production and application of nitrogen fertilizer
- tillage, planting, and harvesting the crop

- marketing, drying, and storing the crop
- converting the corn to ethanol at the plant
- transporting ethanol to the gas pump
- burning the fuel in a motor vehicle

As currently proposed, the results of the LCA performed on various types of fuel will be compared with a baseline number. The Energy Independence and Security Act of 2007 (EISA) provides for the baseline level to be the GHG emissions associated with petroleum-based fuels in 2005 for the renewable fuel standard (RFS) rulemaking.

Under a cap-and-trade policy, the estimated GHG emissions associated with various fuels will help to determine the relative cost of using the fuels. Assuming that the emissions caps are binding (which seems likely), then fuels that are deemed to produce fewer GHG emissions per mile driven will be more attractive to produce and use. Although the costs of the policy would ultimately be borne by consumers, it would be the fuel producers who actually buy and sell the carbon credits. The per-unit cost associated with GHG emissions would become a factor in the overall cost of producing the fuel.

Direct Emissions

In reality, each gallon of ethanol produced may have a different amount of GHG emissions, depending on how much fertilizer was used, the tillage practice used to produce the corn, how much the corn was dried, etc. The LCA will need to identify a representative amount of GHG emissions to cover the spectrum of actual practices.

The level of nitrous oxide emissions associated with corn production has an overriding influence on the LCA results, since the GHG impact of nitrous oxide emissions is considered to be several hundred times worse than carbon dioxide emissions. The type of energy used by the ethanol plant is another major variable, as electricity from a coal-burning power plant has much higher GHG emissions than from a plant that burns natural gas, for example.

A complete LCA will incorporate not only GHG emissions associated with the production of a fuel, but also any potential GHG mitigation that occurs along the way. The production of corn results in carbon sequestration into the ground, which helps to offset the GHG emissions mentioned previously. In fact, studies have found that corn-based ethanol can produce 22% less GHG emissions (on a carbon dioxide-equivalent basis) than petroleum-based gasoline, due largely to the fact that carbon is sequestered in the production of corn. Production of cellulosic ethanol from perennial crops, such as switchgrass or miscanthus, fares even better in such analyses because the emissions associated with growing the feedstock are much lower. Studies have shown that cellulosic ethanol can provide up to a 91% reduction in GHG emissions compared with petroleum-based gasoline.

New technologies continue to reduce the direct carbon footprint (GHG emissions) of biofuels. With the advent of eight-way stacked traits in 2009 and 2010, seed technology companies suggest a 10% increase in corn yields is possible. In addition, advances in drought tolerance as well as better nitrogen utilization in corn plants are on the horizon. Technologies are also advancing in ethanol processing, with a reduction of 19% in British thermal units (BTU) requirements over the last four years (2004–07). Ethanol yields per bushel of corn are also continuing to improve, growing 6.4% from 2001 to 2007. Water consumption by ethanol plants is down 26.6% from 2001 to 2007. Over the next few years, emerging technologies such as fractionation of corn are expected to be increasingly adopted. Fractionation is the process of separating a corn kernel into its endosperm, germ, and bran. The germ can be used to produce food grade corn oil as well as food proteins. The fiber from the bran can be used to help fuel the ethanol plant or as a feedstock for cellulosic ethanol. Using the fiber in a solid fuel burner is estimated to reduce natural gas requirements by 60%. Other technologies such as a "no-cook process" prior to fermentation offer savings of 8–15% in natural gas prices. Technologies are also on the horizon to move ethanol yields per bushel of corn from current levels of 2.81 gallons per bushel to 3.1 gallons per bushel in the next 10 years, with

an upside potential of 3.3 gallons per bushel. With the technology coming online in corn and corn ethanol production, the carbon footprint is only set to improve significantly in the next 10 years, whereas new feedstock sources in the petroleum industry such as oil sands further degrade petroleum's carbon footprint.

Indirect Emissions

The emissions described above can be called the direct emissions associated with biofuel production. Some recent studies have suggested that some indirect GHG emissions also should be included in the LCA. These indirect emissions are those associated with changes in land use in other countries caused by the use of crops for biofuels.

A simple example of the argument for including "indirect land-use change" goes as follows:

- Use of corn for ethanol in the United States causes corn prices to rise, which causes farmers to grow more corn and less soybeans
- U.S. soybean exports fall as a result of reduced plantings, and corn exports fall because more corn is used for ethanol.
- The reduction in U.S. corn and soybean exports suggests that other countries will need to grow more corn and soybeans to fill the gap left by the loss in U.S. exports.
- Land that is currently unused (forest or grassland) is brought into production, possibly in environmentally sensitive areas.

When forest or grassland is converted into cropland, carbon that had been sequestered in the plant material and in the soil is released. The amount of carbon released depends on the type of land being cleared, and potentially how it is cleared. Clearing of forests releases more carbon generally than clearing grassland (due to the amount of carbon stored in the plant matter), while clearing forested peatland is worse still (due to the amount of carbon stored in the soil).

Some argue that if ethanol receives "credit" for carbon sequestered in the production of the feedstock, then it should also be charged a "debit" for this initial release of carbon from the newly-cleared land. It is further argued that this initial carbon release may dwarf future

carbon sequestration from crop production, causing the LCA to show a large net increase in GHG emissions from biofuels relative to the petroleum baseline.

The argument in favor of including indirect land-use change may have some intuitive appeal, but there are some major impediments to its inclusion in an LCA, especially one to be conducted in the near future. LCA is being used to actually quantify GHG emissions, and the scientific literature shows a huge variation in estimates of carbon release from land clearing in general, on the order of 50% plus or minus. In addition, as mentioned previously, the clearing of different types of land will generate different amounts of carbon release. Further, it is questionable whether the necessary data are available to determine what types of land are being cleared for agricultural use and by which methods.

Another challenge in quantifying the GHG effects of biofuels is that it needs to only consider land-use changes actually related to increased biofuels production. It would be neither fair nor accurate to attribute all current and future land clearing to biofuels, considering the increases in world demand for crops for other purposes. In addition, studies done so far tend to assume that patterns of future land conversion will follow past patterns, neglecting the possibility of policy initiatives to steer land development away from areas of greatest environmental impact, such as tropical rain forests.

Considering the changing world policy and agricultural environment, the sparse and unreliable data on land-use change, the multiple drivers of land-use change, and the considerable ambiguity in measuring GHG emissions associated with land-use change, any assignment of GHG emissions from indirect land use would be suspect at best. While the EPA is under a directive to measure indirect land-use effects from biofuels production, in this case, the policy appears to be ahead of the science in regulating what science cannot yet measure with any degree of certainty.

Estimating the Agricultural Response

In the early discussions of LCA approaches, it appears the EPA intends to use established models of U.S. and international agricultural markets to estimate future land-use effects associated with increased use of biofuels. The use of such models is fairly standard procedure in estimating potential policy effects. One potential problem with using such models is that the parameters were estimated based on historical prices, and using those parameters to project markets forward in an environment of higher prices may yield inaccurate results. In particular, the models will be prone to overstate the supply response to higher responses, and in turn overstate potential conversion of land into crop production.

The key parameter in the modeling of the response of the agricultural sector is yield growth. This will ultimately have a huge influence on the amount of land needed to satisfy increasing world crop demand. With all else being equal, higher yield growth translates into lower land requirements. Any study to be used in an LCA will need to account for recent increases in yield growth for corn and yield-improving technologies that are soon to be released, which may reduce or eliminate the need for any land conversion.

Conclusion

In a cap-and-trade regulatory environment, it would be advantageous to have a low GHG-emissions "score," as determined by the EPA's life cycle analysis. Producers of transport fuels with low GHG emissions not only would need to buy fewer carbon credits, they could be in a position to sell carbon credits to their competitors who are still producing fuels from petroleum.

Since the EPA has not yet announced exactly how its LCA will be conducted for the RFS2 rulemaking, for now the best way for the industry to prepare is to be aware of potential issues associated with various approaches to LCA and what parameters will have the greatest effect. Foremost among these issues is the inclusion and methodology used to calculate indirect land use associated with biofuels. While the EPA is under a directive to measure

indirect land-use effects from biofuels production, in this case, the policy appears to be ahead of the science in regulating what science cannot yet measure with any degree of certainty.

Direct GHG emissions from biofuels production continue to decrease with new technologies. Technologies and practices that can further improve the carbon footprint for ethanol production include:

- Reduced tillage and better nitrogen application at the farm
- Rapidly increasing corn yield, perhaps a 10% step in yields in 2009 or 2010
- Use of natural gas instead of coal as the energy feedstock for ethanol plants and the increased use of biomass as the energy feedstock replacing both natural gas and coal
- Adoption of fractionation technology
- Production process change requiring less energy such as the "no-cook process"
- Improved ethanol yield, possibly reaching 3.1 gallons per bushel on average in the next decade.

Some factors to watch in proposed LCA analysis include:

- Comparison point with petroleum—GHG analysis should be at the margin
  - In producing the next unit of petroleum-based gasoline, what are the feedstocks?
  - GHG emissions from increasing tar-sand petroleum production are far worse than conventional petroleum.
  - The carbon footprint for ethanol continues to improve.
- Crop yield growth and input technology assumptions:
  - Corn yield growth has accelerated over the last 10 years compared with the previous 20 years.
  - Current yield growth may suggest little or no need for increased land area in foreign countries. Despite record ethanol use in 2007/08, corn exports were also at record levels.
  - Technology improvements in nitrogen utilization will dramatically improve the farm GHG footprint.
- Ethanol yield growth assumptions:
  - The 2007 Renewable Fuels Association survey reports average ethanol yields at 2.81 gallons per bushel, which is consistent with yields derived from the

Energy Information Administration (EIA) ethanol production estimates and corn used for ethanol in dry mill plants.

- o Future ethanol yield growth must be considered in the analysis, with 3.1 gallons per bushel a realistic yield within the next 10 years and an upside potential of 3.3 gallons per bushel.

- Ethanol-processing technology continues to improve:

    - o Technology in the pipeline includes fractionation, the "no-cook process," removal of corn oil from distillers' grains, the burning of corn fiber as feedstock energy for the plant, etc.

    - o All of these technologies reduce the carbon footprint of biofuels.

- Almost any industry creates indirect GHG emissions and the petroleum industry is no exception. One example is the indirect GHG emissions associated with the use of the U.S. military to protect and ensure access to petroleum supplies. These indirect emissions could be estimated with more reliable data than the GHG emissions associated with indirect land use assigned to biofuels.

I. INTRODUCTION

The purpose of this paper is to examine the potential effects of a low carbon fuel standard (LCFS) on the U.S. biofuels industry and review both the U.S. Environmental Protection Agency (EPA)'s and California's proposed life cycle analysis (LCA) approach to quantifying the greenhouse gas emissions (GHG) associated with the production of renewable fuels. Since LCFS policies are still in the development process, the approaches by California, other states, and the EPA are slightly different; however, the overriding concepts are similar. Broadly, LCFS policies are designed to reduce human-caused GHG emissions from an established baseline level in the past. Scientists have postulated that these GHG emissions are causing global warming. GHG emissions arise from several sources, but transportation and energy production are the primary sources.

In response to rising concern over the potential climatic effects of GHG emissions, the U.S. Congress is expected to consider legislation to control GHG emissions via a "cap-and-trade" policy. Under such a policy, the government would set allowances for total annual emissions of GHGs by companies in various industries. Companies that exceed their allowances would be allowed to offset the additional emissions by purchasing "carbon credits" from owners of unused carbon allowances. Instead of measuring actual carbon releases on a real-time basis (which would be impossible, or certainly impractical), a system would need to be devised to assign a level of carbon emissions associated with various industrial activities.

To establish GHG emissions in the transportation sector, LCA was introduced to measure the GHG emissions associated with each stage in the life cycle of the production of a particular fuel from the materials used in recovery or production of fuel feedstocks, transportation of feedstocks, and the physical production of the fuel to the transportation and ultimate consumption of that fuel. Initially, LCA focused on the direct measurable effects of the GHG emissions associated with each stage of the process. In the case of ethanol, after

some initial controversy, Michael Wang and others effectively demonstrated that corn ethanol could help reduce GHG emission about 20% for ethanol plants fueled with natural gas. This result was drawn into question by other scientists who argued that Wang and others did not consider the indirect effects of land-use change (LUC) resulting from increased U.S. ethanol production. In calculating the indirect effects of LUC, these scientists argue that the GHG emissions associated with bringing new land into crop production because of increased usage of crops for production of biofuels ultimately results in biofuels significantly increasing GHG emissions rather than reducing them.

For ethanol, this argument has direct implications. Considering this result in the context of the Energy Independence and Security Act (EISA) of 2007 creates an alarming situation for future production of corn ethanol. EISA requires conventional biofuels (corn-based ethanol) to provide a 20% reduction in direct and indirect GHG emissions (although the EPA has the ability to adjust this down to 10%). It is important to note that this requirement applies to all new ethanol plants coming online beginning in 2009 (the EPA statement in the Federal Register FRL-8528-9). Even with only a 10% reduction in GHG emissions required for corn ethanol, GHG emissions associated with LUC based on attorney Timothy Searchinger's work would suggest that corn ethanol could not meet the 10% reduction criteria (Searchinger et al., 2008). The implication of not meeting the GHG emission criteria is that future corn ethanol might not be classified as a renewable fuel under EISA and could not be used to meet required GHG reductions in the proposed LCFS in California.

Clearly, the methodology used in LCA is very important to the future of corn ethanol. The EPA's proposed LCA approach can be broken down into quantifying the direct GHG emissions associated with producing a particular biofuel and indirect emissions associated with LUC. Given a specified technology level in the production process, sources of energy feedstocks, the biofuels feedstock, and the type of vehicle the fuel will be used in, various environmental models can be used to estimate the amount of direct GHG emissions. At the

risk of overemphasizing the point, these emission estimates are specific to the assumptions regarding the technology, feedstocks, and ultimate use of the fuel. Given these assumptions, estimating the direct GHG emissions associated with the production of a particular biofuel is a fairly well-established process. The process of establishing indirect GHG emission is not nearly as well researched and developed, and it suffers from the lack of a consistent process and large potential errors in estimation.

Under a cap-and-trade policy, the estimated GHG emissions associated with various fuels will help to determine the relative cost of using the fuels. Assuming that the emissions caps are binding (which seems highly likely), then fuels that are deemed to produce fewer GHG emissions per mile driven will be more attractive to produce and use. It is important to note, however, that a pure cap-and-trade policy would not absolutely require the use of one fuel or another. Although the costs of the policy would ultimately be borne by consumers, the fuel producers would actually buy and sell the carbon credits. The per-unit cost associated with GHG emissions would become a factor in the overall cost of producing the fuel. Depending on the price of carbon emissions (to be determined by the broader supply and demand of carbon emission credits), a fuel that has relatively high GHG emissions could still be cheaper to the consumer if its production costs are low enough and carbon credits are fairly low-priced.

With all else being equal, in a cap-and-trade regulatory environment, it would be advantageous to have a low GHG-emissions "score," as determined by the EPA's life cycle analysis. For example, in a preliminary analysis of GHG emissions associated with various fuels (excluding indirect LUC), the EPA estimated that corn ethanol on average emits 22% less GHGs than conventional gasoline produced from petroleum, while cellulosic ethanol would emit 91% less GHGs. The final results of the EPA's LCA will differ from this, but the biofuels industry would achieve a significant cost advantage if gasoline is found to emit 10 times as much GHGs as cellulosic ethanol. Producers of cellulosic ethanol not only would

need to buy fewer carbon credits, they could be in a position to sell carbon credits to their competitors who are still producing fuels from petroleum.

To make this review more easily understood, some background information on life cycle analysis is presented throughout the review to help those less familiar with the subject.

II. BACKGROUND ON GHGS

Greenhouse Gases Defined

GHGs are naturally occurring and human-made chemical compounds. In the earth's atmosphere, these gases allow sunlight to enter freely, but impede the heat (infrared radiation) that is reflected off the surface of the earth from escaping into space. As these gases accumulate in the atmosphere, theory suggests that the temperature of the Earth's surface will begin to rise, creating a "greenhouse" effect. There are several types of chemical compounds that have the potential to be greenhouse gases, and their ability to impede heat from escaping the earth's surface varies greatly by type of gas. GHGs are classified using a scale that measures their ability to impede heat from escaping the earth's surface. As developed by the Intergovernmental Panel on Climate Change (IPCC) in its Second Assessment Report released in 1996, this scale measures the global warming potential of each gas relative to carbon dioxide (CO_2). As Table 2.1 indicates, some GHGs have much larger global warming potential. For example, CO_2 has a much lower global warming potential, reflecting less heat on the surface of the earth and contributing less to the "greenhouse" effect than HFC-23 with a global warming potential of 11,700.

Sources of GHGs

The most potentially damaging of the greenhouse gases, hydrofluorocarbons

Table 2.1 Global Warming Potentials By Type of Greenhouse Gas

Gas Type	Global Warming Potential*
CO_2	1
CH_4	21
N_2O	310
HFC-23	11700
HFC-32	650
HFC-125	2800
HFC-134a	1300
HFC-143a	3800
HFC-152a	140
HFC-227ea	2900
HFC-236fa	6300
HFC-4310mee	1300
CF_4	6500
C_2F_6	9200
C_4F_{10}	7000
C_6F_{14}	7400
SF_6	23900

Source: EPA Report, "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2005" April 2007.

(HFCs), perfluorocarbon (PFCs), and sulfur hexafluoride (SF_6), are synthetic chemicals developed primarily for the replacement of ozone-depleting gases. These gases are also created in aluminum and magnesium production, semiconductor manufacturing, and electrical transmission and distribution systems. Despite their high levels of global warming potential, these gases are responsible for only 2.2% of the total human-generated (anthropogenic) greenhouse gas emissions reported by the EPA in 2005.

The remaining three gases, carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), are responsible for 83.9%, 7.4%, and 6.5% of total anthropogenic GHG emissions, respectively, based on EPA data for 2005. Therefore, these gases are the primary focus of reducing GHG emissions. The primary source of CO_2 emissions is fossil fuel combustion, which accounted for 79% of CO_2 emission in 2005. Fossil fuel combustion may be further broken down into transportation use, industrial use, residential use, and commercial use, representing 33%, 27%, 21%, and 18% of fossil fuel combustion in 2005, respectively. Within these four categories, direct consumption of fossil fuels accounted for 59% of CO_2 emissions while electricity generation accounted for 41% of CO_2 emissions.

The primary sources of CH_4 gas emissions are landfills (24%), enteric fermentation (21%), natural gas systems (21%), coal mining (10%), manure management (8%), and petroleum systems (5%). The primary source of N_2O emissions is soil-management activities, particularly the use of nitrogen fertilizer. Soil-management activities account for 78% of N_2O emissions.

Trends in GHG Emissions

The Intergovernmental Panel on Climate Change (IPCC) reports that global concentrations of GHG emission from CO_2, CH_4, and N_2O have increased by 35%, 143%, and 18%, respectively, over 1750–2004. Over the last 15 years, there has been considerable variance in GHG emissions in the United States, ranging from a decline of 1.7% in 2001 to an

increase of 4.0% in 1996. On average, U.S. GHG emissions appear to be growing at an annual rate of 1% per year.
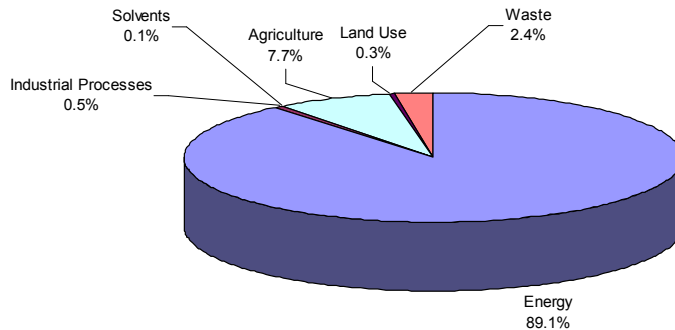
Measurement of GHG Emissions

GHG emissions are typically measured in teragrams of carbon dioxide equivalent denoted as Tg CO_2 Eq. A teragram is equivalent to one million metric tons. For any GHG, the teragrams of carbon dioxide equivalent is found by multiplying the teragrams of the gas by its global warming potential (see Table 2.1). The values found in Table 2.1 are under continuous revision by the IPCC. In 2001, the IPCC revised the estimated global warming potential of CH_4 up by 10% to account for the indirect GHG emissions associated with the release of tropospheric ozone and stratospheric water vapor. The global warming potential of N_2O was revised down 5%. The IPCC notes that the global warming potential ratings typically have an uncertainty of plus or minus 35%.
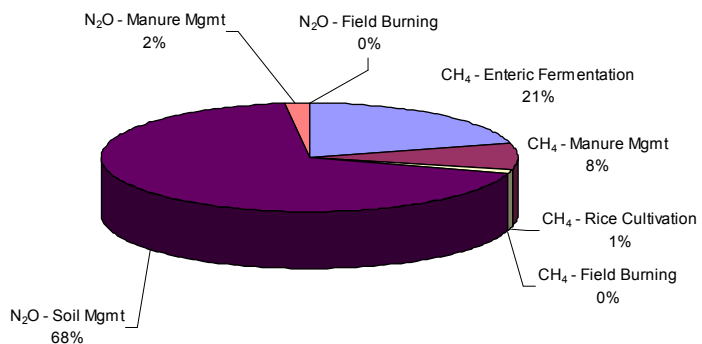
III. HOW DOES AGRICULTURE CONTRIBUTE TO GHG EMISSIONS?

The EPA attributed 7.7% of anthropogenic GHG emissions to agriculture in 2005 compared with nearly 89.1% from the energy sector, making agriculture the second-leading cause of GHG emissions, but a very distant second (see Figure 3.1). Most of agriculture's GHG emissions are associated with soil management and the enteric fermentation in beef and dairy cattle production. Over two-thirds of the emissions associated with soil management are associated with the use of nitrogen fertilizer for crops such as corn and wheat (see Figure 3.2).

Figure 3.1 Total 2005 US Greenhouse Gas Emissions 7260.4 Tg CO_2 Equivalent

Solvents 0.1%
Industrial Processes 0.5%
Agriculture 7.7%
Land Use 0.3%
Waste 2.4%
Energy 89.1%

Figure 3.2 2005 US Greenhouse Gas Emissions from Agriculture 536.3 Tg CO_2 Equivalent

N_2O - Manure Mgmt 2%
N_2O - Field Burning 0%
CH_4 - Enteric Fermentation 21%
CH_4 - Manure Mgmt 8%
CH_4 - Rice Cultivation 1%
CH_4 - Field Burning 0%
N_2O - Soil Mgmt 68%

IV. HOW CAN AGRICULTURE HELP REDUCE GHG EMISSIONS?

Historically, agriculture's contribution to reducing GHG emissions was focused on cultivating plants that sequestered more carbon, levels of nitrogen application and methods of nitrogen application, reduced tillage systems, and new technology.

With the advent of biofuels, agriculture has the potential to provide an even larger contribution to reducing GHG emissions associated with the largest overall category of GHG emissions, fossil fuel combustion.
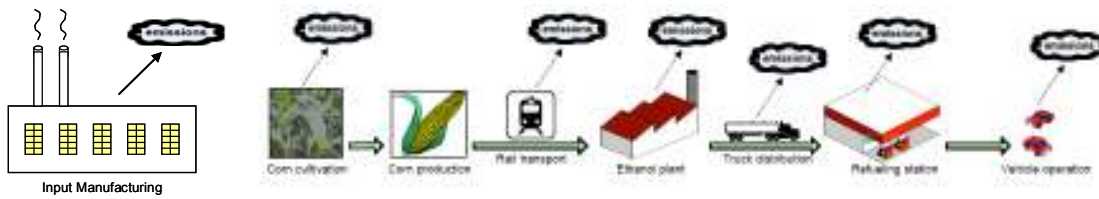
V. WHAT IS LIFE CYCLE ANALYSIS?

The effort to reduce the potential contribution of transportation fuels to global warming has led policymakers to focus on the emissions of GHGs from various forms of fuels. Initial efforts focused on tailpipe emissions, but more recently the focus has shifted to so-called "life cycle analysis (LCA) of fuels," which includes the GHG emissions associated with the production and transportation of the fuel to the vehicle (well-to-tank) as well as the emissions associated with burning the fuel in the vehicle (tank-to-wheel). The total result is referred to as well-to-wheel (WTW) analysis. As defined by the Energy Independence and Security Act of 2007 (EISA):

> The term 'lifecycle greenhouse gas emissions' means the aggregate quantity of greenhouse gas emissions (including direct emissions and significant indirect emissions such as significant emissions from land use changes), as determined by the Administrator, related to the full fuel lifecycle, including all stages of fuel and feedstock production and distribution, from feedstock generation or extraction through the distribution and delivery and use of the finished fuel to the ultimate consumer, where the mass values for all greenhouse gases are adjusted to account for the relative global warming potential.

Figure 5.1 illustrates the potential sources of direct GHG emissions from ethanol production for the entire life cycle. The process begins with GHG emissions associated with the production of inputs used to grow corn. These emissions are primarily associated with the production of nitrogen fertilizer and the fossil fuels used in the input production process. In the next step, GHG emissions arise in the production of corn primarily through nitrogen application and the use of fossil fuels for field tillage and application of fertilizer and chemicals, and delivery of the grain to the terminal. GHG emissions then arise from the transportation of the grain from the terminal to the ethanol plant. At the ethanol plant, GHG emissions primarily arise from use of fossil fuels for the plant's energy. The amount of GHGs created varies considerably depending on the source of fuels used. The last three stages of the life cycle apply to the distribution, sales, and actual use of the ethanol in cars.

Figure 5.1 Sources of greenhouse gas emissions from ethanol

Source: Adapted from Mark Delucci's "Lifecycle Analysis of Biofuels" 2006

VI. APPROACHES TO BIOFUELS LIFE CYCLE ANALYSIS

U.S. EPA

As of October 10, 2008, the EPA had not released its final approach to LCA for biofuels. Clearly, the discussion continues to evolve the EPA methodology, but as of yet a clear methodology has yet to emerge. In a May 2008 presentation, Sarah Dunham, director of the Transportation and Climate Division of the EPA, discussed a potential approach the EPA might take to biofuels life cycle analysis. Under the potential approach, the EPA would use a comprehensive agricultural sector model of U.S. agriculture to determine the GHG emissions associated with increased biofuels production. This model is known as the Forest and Agricultural Sector Optimization Model (FASOM). FASOM captures both carbon sequestration and carbon losses over time. The EPA would calculate the indirect effects of land-use change by utilizing global structural econometric models of the agricultural sector maintained by the Food and Agricultural Policy Research Institute (FAPRI) division of the Center for Agriculture and Rural Development (CARD) at Iowa State University. Land-use change would be calculated based on measuring the effects on exports and planted area for a policy change relative to a reference case. The change in total crop acreage would be converted to GHG emissions, but the EPA did not offer specific details on the conversions used in this process. The EPA suggests it will use "process models from USDA" to calculate emissions from ethanol processing. Finally, the EPA proposed to utilize the GREET model from the Department of Energy's Argonne Laboratory to calculate emissions associated with feedstock and ethanol transportation.

Since May, other approaches have been discussed in sketchy detail by the EPA. The model maintained by researchers at Purdue University's Global Trade Analysis Project (GTAP) has been suggested as an alternative method to CARD-FAPRI's model for calculating indirect land-use change. In addition, satellite photo analysis by the nonprofit rural development and

resource management group Winrock over 2001–04 is being discussed as a method for measuring deforestation, although there appears to be little information on how this might be related to biofuels, particularly since the industry was quite small during that period. The proposed rules on LCA are expected to be release at the end of October 2008 but may be delayed.

Given the relative importance and magnitude of indirect greenhouse gas emissions suggested by other studies, this review will primarily focuses on land-use change with a cursory discussion of the direct GHG emissions associated with the production of biofuels.

California

The California Air Resources Board (CARB), the division of the California Environmental Protection Agency charged with implementing the state's low carbon fuel standard (LCFS), released a draft of its policy framework in mid-October 2008. Many of the major portions of the framework were already mostly established already, but some elements, such as the quantification of carbon emissions associated with indirect land-use change, are still being developed.

As previously cited, studies have indicated that well-to-wheel GHG emissions from corn-based ethanol are approximately 22% lower than conventional petroleum-based gasoline without including any effects from indirect land-use change. More specifically, on average corn-based ethanol generated emissions of 75 grams of CO_2 equivalent per megajoule of energy (gCO_2/MJ), while petroleum-based gasoline generated 96 gCO_2/MJ. CARB's draft study of the effects of indirect land-use changes attributes additional GHG emissions of 35 gCO_2/MJ to corn-based ethanol. The addition of indirect land-use changes boosts the total GHG emissions of corn-based ethanol to 110 gCO_2/MJ, 15% higher than those of gasoline.

The indirect land-use scenarios modeled the influence of an increase in corn-based ethanol production of 13.25 billion gallons from 2001 to 2015, in line with the EISA of 2007. The

GTAP model was used, and the study projected total GHG emissions over 30 years. On average, the analysis predicted that 1.6 million hectares (3.96 million acres) of land in the United States would be converted to cropland. The conversion of forest land accounted for almost one-third of the total, with the rest coming from pasture land. The analysis predicted that worldwide conversion of land (including the United States) would be 4.2 million hectares, with 19% coming from forests and the remaining 81% from pastures.

CARB's presentation of the draft policy framework makes clear that the results are preliminary, and therefore subject to a comment period. In addition, many potential fuel pathways need to be evaluated, including cellulosic ethanol. Given the information provided thus far, cellulosic ethanol should fare much better in similar analyses. CARB states that a biofuel will likely have no land use change when it:

- is not derived from crops;
- is derived from cover crops, or similar types;
- is derived from crops grown on land not supporting other crop growth.

The draft results of CARB's analysis do not look favorable to corn-based ethanol, but CARB's presentation of the results acknowledges some potential problems with the analysis, or at least areas that can be called into question. The biggest drawback of the analysis, at least in terms of using the numbers to guide policy analysis, is the wide variation in the results and the high degree of sensitivity to changes in input parameters.

As mentioned in an earlier section of this report, assumptions regarding crop yields are a major factor in the results. Basically, higher crop yields translate into less acreage required to produce crops. In the context of this analysis, less acreage required to produce crops means less area converted to crop production due to increased corn demand, and therefore, lower GHG emissions attributed to increases in U.S. production of corn-based ethanol. The CARB

report shows the results of sensitivity analyses on some key input variables, illustrated in the following table:

Sensitivity Analysis Results

Input Variable	Input Variable Ranges		Output Variable Ranges (gCO2/MJ)	
	Low Value	High Value	From Low Input Value	From High Input Value
Corn Yield Elasticity	0.1	0.6	57	29
Elasticity of Harvested Acreage Response	0.5	0.5	Not subjected to sensitivity analysis	
Elasticity of Land Transformation across Cropland, Pasture and Forestry	0.1	0.3	30	39
Elasticity of Crop Yields with Respect to Area Expansion	0.25	0.75	88	20
Trade Elasticity	1 S.D. Below	1 S.D. Above	37.1	36.5

Source: CARB, "Life Cycle Analysis and Land Use Change Effects", Oct. 15, 2008

The assumed productivity of land being brought into production produced the most variability in the results, with a range of 20 gCO_2/MJ to 88 gCO_2/MJ. Only one variable at a time was changed in the sensitivity analysis; variations in two or more variables would produce an even wider range of potential results. Reducing the GHG emissions from indirect land-use change to 20 gCO_2/MJ, when added to the 75 gCO_2/MJ attributed to corn-based ethanol without considering indirect land-use change, would bring the total GHG emissions to 95 gCO_2/MJ, about equal to that of gasoline.

Other potential sources of variability in the analysis that were not subjected to sensitivity analysis were the predictions of land conversions (whether United States or rest of world, forest vs. pasture), and what carbon-release and sequestration factors to use for land being converted. The proportion of land conversion that came from forest was fairly low in the draft

study, which produces a lower GHG emissions "score." The issue of where land conversion occurs is directly related to the issue of crop yields, since the assumed yield on converted land is a function of overall yields in the country where the land is being converted. Therefore, more land converted in higher-yielding countries and regions, such as the United States, Canada, or the European Union, will translate into less total need for land conversion.

The biggest potential source of variability, or outright error, in the results, though, is probably in the estimates of carbon emissions associated with land clearing. As pointed out earlier in this paper, estimates of carbon flux vary dramatically, as stated in a March 2008 article in *Eos* magazine, which was co-authored by one of the sources used by a researcher at the Woods Hole Research Center (the source of the carbon-release data used in the analysis of indirect land-use change):

> North America's forests are thought to be a significant sink for atmospheric carbon. Currently, the rate of sequestration by forests on the continent has been estimated at 0.23 petagrams of carbon per year, though the uncertainty about this estimate is nearly 50%. This offsets about 13% of the fossil fuel emissions from the continent [*Pacala et al.*, 2007]. However, the high level of uncertainty in this estimate and the scientific community's limited ability to predict the future direction of the forest carbon flux reflect a lack of detailed knowledge about the effects of forest disturbance and recovery across the continent. (Goward, et al.)

VII. DIRECT GHG EMISSIONS ASSOCIATED WITH BIOFUELS

One of the major selling points of biofuels is the environmental benefit of reduced GHG emissions compared with conventional petroleum-based gasoline. The production process of biofuels helps to illustrate the complex nature of life cycle analysis (LCA). The predominant form of biofuel currently used in the United States is corn-based ethanol. Its production first requires the production of corn, which generates GHG emissions to power farm equipment, transport purchased inputs to the farm, transport the grain from the farm to market, dry the grain, etc. Producing fuel ethanol from corn also requires energy, mostly electricity, and then ethanol must be transported to be blended with gasoline as a fuel. Many studies have found that the GHG emissions associated with corn-based ethanol are more than offset by the carbon that is removed from the air by the corn as it grows. By this calculation, GHG emissions associated with corn-based ethanol have been estimated as being 20% lower than gasoline. Other studies have shown that ethanol produced from cellulosic plants, such as switchgrass, could achieve much greater reductions in GHG emissions. Since the potential feedstocks for cellulosic-based ethanol are mostly low-input perennials, the GHG emissions associated with production of the feedstocks are lower.

The GHG emissions associated with corn-based ethanol production vary due to many factors, such as the tillage method used to produce the corn, corn yield, the efficiency of the ethanol plant in converting corn to ethanol, and the method of generating electricity to power the ethanol plant. The last factor has emerged as a big variable in GHG calculations, as electricity produced from coal-burning plants will produce far more GHGs than from natural gas-burning plants, for example. Most studies of GHG emissions tend to take an average of actual practices to arrive at estimates.

VIII.   MEASURING DIRECT GHG EMISSIONS WITH GREET

FASOM and GREET

Per the directive of this analysis, an evaluation of the GREET model and its ability to measure the direct GHG emissions associated with biofuels and petroleum production are presented here. Nevertheless, the EPA indicates it will use the FASOM model in assessing GHG emissions, so the FASOM model merits a few comments. FASOM is a regional dynamic, nonlinear programming model of the forestry and agricultural sectors in the United States. Crop prices are endogenous within the FASOM model, dynamically adjusting the crop mix as demand for crops changes. This allows FASOM to reflect the growing demand for biofuels, subsequent changes in crop mix, and ultimately the effects on GHG emissions. Since the FASOM model is more specific to agriculture and includes significantly more parameters associated with GHG emissions in agriculture, it is more appealing than GREET because the model can be more finely tuned to reflect changes in agricultural management practices and the production of biofuels feedstocks that affect GHG emissions. The 2005 documentation of the FASOM model indicates the model can determine the effects on agriculture's GHG emissions from changes in fossil fuel usage, chemical usage, fertilization practices, livestock herd, ruminant livestock feeding and rate of gain, manure management, rice production techniques, and legume acreage. More generally, the model will also capture changes in GHG gas emissions from U.S. agriculture due to crop mix change, irrigated-versus dry-land crops, regional location of crops, regional size and location of the livestock herd, composition of feed ingredients, consumption patterns, processing patterns, and regional trade patterns.

FASOM struggles with some of the same challenges encountered by other agricultural models in that much of the estimation and calibration of FASOM was done over periods of low commodity prices. The FASOM documentation notes on page 70, "Thus the crop mixes

will not be an accurate representation either if the expected prices confronted by the model are well outside the historical range or if the situation to be examined substantially revises the production possibilities." The implication is that the FASOM model may not produce results with the same accuracy as historical simulation given the high level of current commodity prices. The other implication is that if FASOM does not capture new technologies it may also provide inaccurate estimates. This is a common problem with all types of models in the current environment, however. It does not appear that the current FASOM model is available for public review, which makes a full assessment of its strengths and weaknesses difficult.

What is the GREET Model?

The GREET model is a publicly available, Microsoft Excel-based model designed to estimate the emissions of the three primary anthropogenic greenhouse gases (CO_2, CH_4, and N_2O) associated with the use of fossil and non-fossil fuels for transportation purposes. The acronym GREET stands for Greenhouse gases, Regulated Emissions, and Energy use in Transportation. The GREET model traces its roots back to the 1980s when Michael Wang at Argonne National Laboratory began his early work in wells-to-wheels analysis, then called fuel-cycle analysis. With its relatively long history of development, the GREET model has undergone many critical reviews with ongoing updates. It has become accepted by many sources as the premiere tool for analyzing GHG emissions from the well to the wheel and continues to be widely used and cited. The most recent release of the GREET model occurred in May 2008 with GREET version 1.8b. This update includes more vehicle types and possible biofuel feedstocks as well as other pathways.

Challenges of the GREET Model

As with all models, GREET faces the constant struggle of keeping up with new technology developments in the biofuels area. New ethanol production technologies, co-products, and energy sources that need to be added to GREET include, but are not limited to:

- Default assumptions for the latest ethanol production technology,
- Displacement value of new co-products (corn oil and protein) via fractionation, and
- Displacement value of corn oil extracted from distillers' grains.

Technologies to produce ethanol from corn and other feedstocks are rapidly changing since the Energy Act of 2005 provided the safety net of a mandate that spurred rapid investment in the ethanol industry. As more and more ethanol plants have been built, the technologies have gotten better and the importance and use of by-products have become more recognized.

GREET Model Parameters

Within the GREET model are a set of parameters that are used to estimate the GHG emissions associated with specific fuel pathways and types of vehicles in which the fuel is consumed. These parameters can be changed to reflect new technologies as they emerge, but the default values are often the easiest place to begin. In his design of GREET, Wang has made considerable efforts to represent current technology in plants as well as to estimate how that technology may look in 2010 and beyond. Technologies are changing rapidly, though, and, as suggested above, new by-products are already on the horizon for corn ethanol. These developments will require continuous review of the parameters used in the model.

There are numerous parameters in the GREET model, so it is important to focus on those with the greatest uncertainty as well as those that have the greatest effect on GHG emissions calculations. The most critical parameters influencing GHG emission calculations with the GREET model are

- GHG emissions from direct land-use change,
- corn yield growth,
- nitrogen fertilization rates,
- the conversion rate of nitrogen in fertilizer to nitrous oxide,
- the source of fuel for ethanol plants,
- the amount of fuel required to produce a gallon of ethanol, and
- the feedstock from which ethanol is made.

Indirect land-use changes are not accounted for within the GREET model.

Direct Land-Use Change

Wang developed his estimate of the GHG emissions from direct land-use change based on a late 1990s study by the United States Department of Agriculture (USDA), which looked at land-use changes associated with corn ethanol production of 4 billion gallons per year (Wang 2007). The study reflected the competition between current crops as well as some conversion of Conservation Reserve Program (CRP) acres. Based on the land-use changes simulated by USDA, Wang estimated CO_2 emissions of 195 grams per bushel of corn, an estimate Wang continues to use in the latest version of GREET (1.8b). The criticism by other researchers and acknowledged by Wang is that this estimate may not be accurate because the quantity of ethanol currently being produced and mandated in EISA (15 billion gallons by 2015) is much larger, requiring more restructuring among crops and potentially more CRP acres.
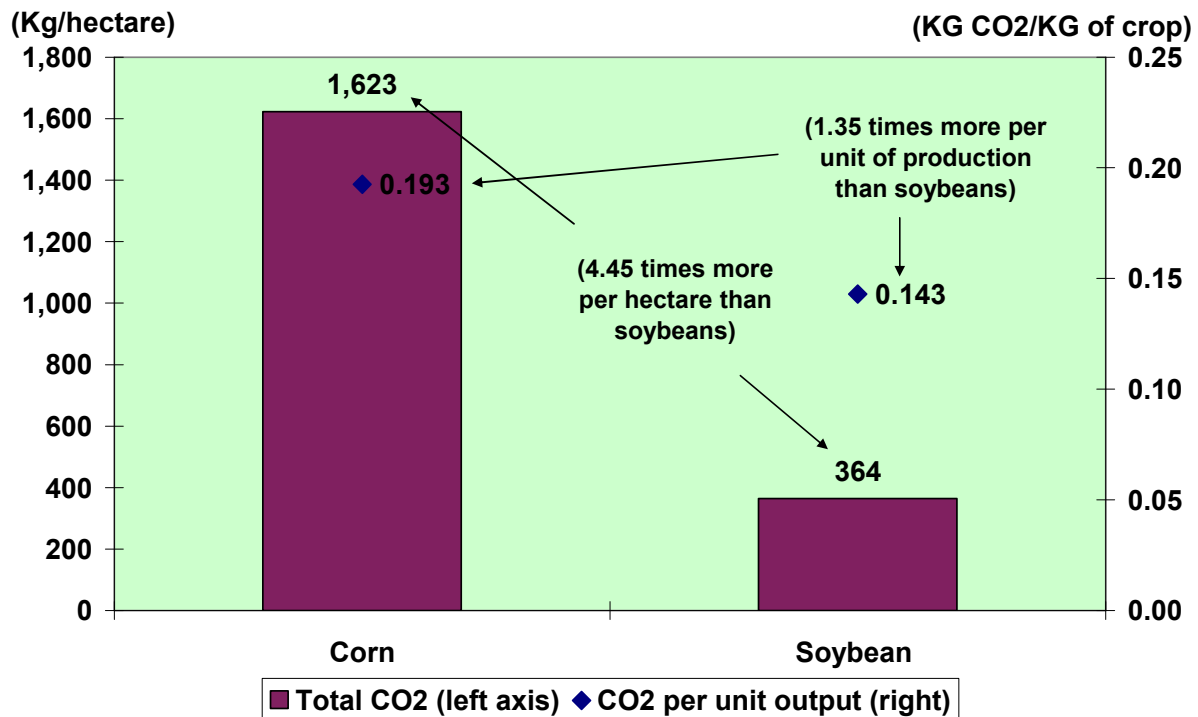
Corn Yield Growth

 Corn yield growth is an important assumption because it reflects the continuous advances in productivity, which translates into lower GHG emission per bushel of corn produced. U.S. average corn yields have doubled over 1970–2008. Nitrogen fertilizer use per acre peaked in 1985 and has been trending lower since then. The combination of these trends suggests significant improvement in GHG emissions per bushel since 1970.

What does the future have to offer for yield growth? As discussed later in this report, the technology pipeline is full and offers the possibility of even faster yield growth than previously experienced as well as improving efficiency with respect to nitrogen fertilization (the biggest source of GHG emissions in growing corn).

Nitrogen Fertilization and Conversion of Nitrogen into N_2O

The carbon footprint of any given crop is significantly affected by the amount of nitrogen applied to the crop and also the intensity of tillage used to establish the crop. Another very important factor is the productivity of the crop being analyzed. Corn, for example, uses significant amounts of nitrogen fertilizer and sees more intensive tillage operations than many crops, particularly soybeans. Beyond the actual level of applied nitrogen (applied N), the emissions of nitrous oxide from applied N and manure can have a dominant influence on the total carbon associated with producing the crop. In this analysis, we use 1.33% of the applied N as the carbon emissions and 1.79% of the applied N through manure for our base levels, but the range of values reported in the literature is dramatic, from near zero to above 10%. Given that one unit of nitrous oxide has a GHG equivalent of 296 units of carbon dioxide, the value assumed can overwhelm the overall analysis. While manure has a higher average emissions factor, in the broad context of U.S. agriculture it is not that important with respect to total fertilized acreage. Use of manure is somewhat regional and situational and currently accounts for about 16% of total nitrogen on corn.

Figure 8.1 US Carbon Dioxide Emissions Per Hectare, 1995-2004 Average
(No Soil Sequestration Assumed)

Given that corn's carbon footprint is dominated by nitrogen, efficient use rates and use of practices that minimize nitrous oxide gas emissions into the air are the most likely targets for improvement. Technologies to reduce nitrogen volatilization have a significant potential to reduce total carbon emissions from corn production. Our analysis indicated that on average 67% of all GHG emissions come from nitrogen fertilizer and emissions from the application of nitrogen. Across all corn acreage, both irrigated and non-irrigated, irrigation accounts for about 5% of carbon dioxide emissions but on an only irrigated-acreage basis. Emissions from pumping water can equate to about 25% of all emissions for corn and nearly

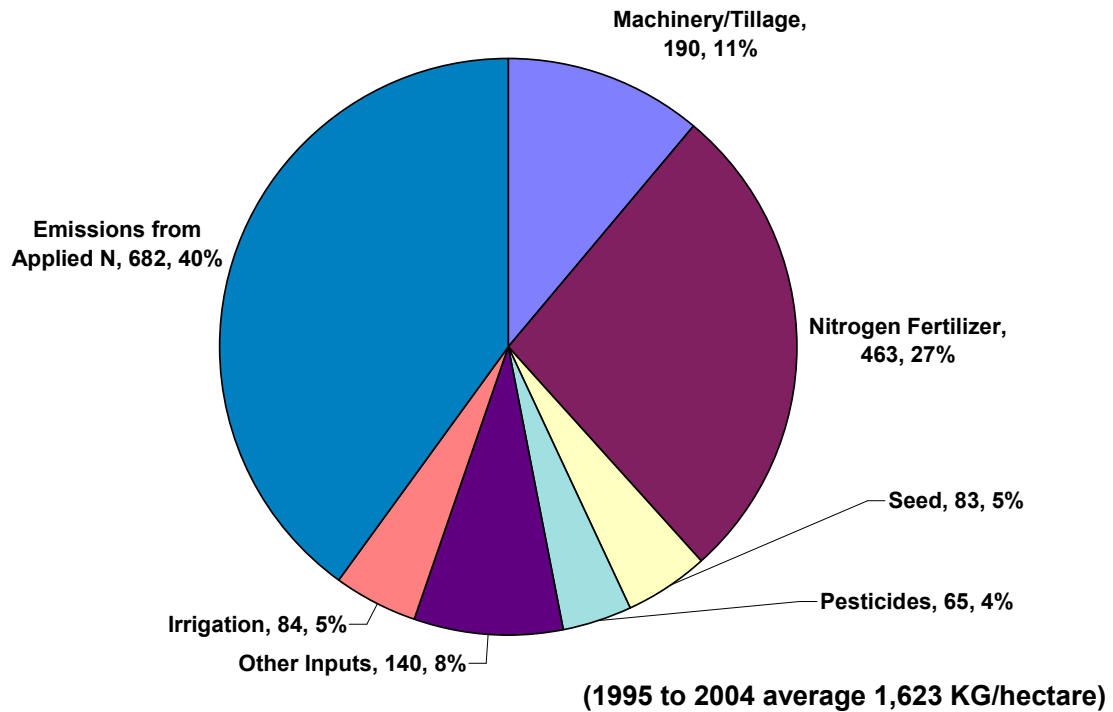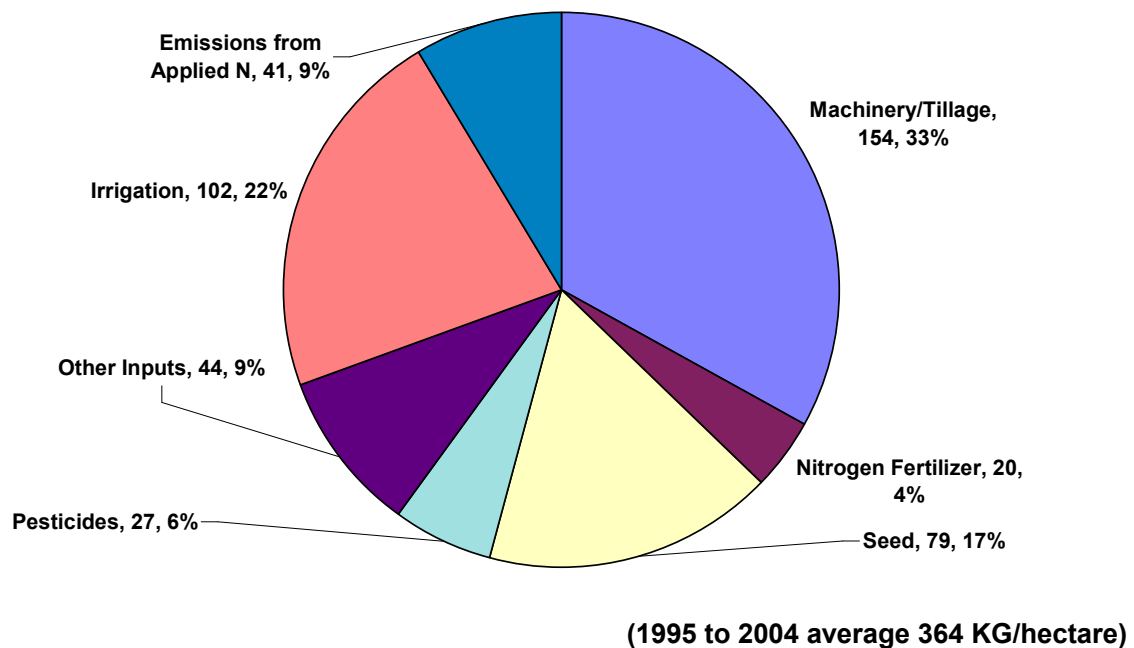**Figure 8.2 United States Greenhouse Gas Emissions from Corn Production, Carbon Dioxide Equivalents and Share**

Machinery/Tillage, 190, 11%

Emissions from Applied N, 682, 40%

Nitrogen Fertilizer, 463, 27%

Seed, 83, 5%

Pesticides, 65, 4%

Irrigation, 84, 5%

Other Inputs, 140, 8%

(1995 to 2004 average 1,623 KG/hectare)

Figure 8.3 United States Greenhouse Gas Emissions from Soybean Production, Carbon Dioxide Equivalents and Share

Emissions from Applied N, 41, 9%

Machinery/Tillage, 154, 33%

Irrigation, 102, 22%

Other Inputs, 44, 9%

Nitrogen Fertilizer, 20, 4%

Pesticides, 27, 6%

Seed, 79, 17%

(1995 to 2004 average 364 KG/hectare)

50% for soybeans. Assuming that other inputs to irrigated crop production are about the same as non-irrigated production, the strong yield differential for irrigated corn keeps the per-unit GHG emissions nearly constant with non-irrigated corn production. Irrigated soybeans, in contrast, more than double their per-unit GHG emissions compared with non-irrigated production.

Nitrogen and Yields

The carbon footprint from the production of inputs used to produce corn is dominated by nitrogen. During the period 1995 through 2004, the average carbon emissions associated with all fertilizer used on corn was 148 kilograms per hectare or 132 pounds per acre. Of this total, 84% was associated with nitrogen, 6% phosphorus, and 5% each potassium and lime. According to the Agricultural Resource Management Survey (ARMS) conducted by the USDA about every five years for corn and other crops, the amount of nitrogen applied by "low cost" corn producers (lowest 25%) is less than the average despite higher-than-average yields. Low-cost producers applied nitrogen on 94% of their corn acreage at a rate of 125 pounds per acre compared with 97% of all acres being treated on average with 134 pounds per acre. Given that low-cost corn producers have considerably higher yields with lower rates of applied fertilizer nitrogen, the nitrogen per unit output is considerably lower than average (20% less) and is nearly half (53%) that of high-cost producers.

Table 8.1 Nitrogen Application Comparison of Low and High Cost U.S. Corn Farms (2001)

	Low Cost	Middle	High Cost	Average
Share Treated (percent)	94	98	97	97
Pounds N Applied per Acre	125	143	125	134
Effective Application Rate N/acre	117.5	140.1	121.3	130.0
Yield (bushels/acre)	163	146	90	144
Pounds N per bushel	0.72	0.96	1.35	0.90

Source: USDA - ARMS Survey - Characteristics and Production Costs of U.S. Corn Farms, 2001

Fuel and other energy products used in the production, drying, and on-farm transport of the crop are another significant source of carbon emissions. Depending on the number of tillage passes and the intensity of tillage used, the amount of fuel used to produce a crop can

change considerably. The values in the table below were developed by West and Marland in their paper "A Synthesis of Carbon Sequestration, Carbon Emissions, and Net Carbon Flux in Agriculture: Comparing Tillage Practices in the United States" produced in 2000. The reference data they used were based on 1995 data.

Table 8.2 Carbon Emissions from Machinery Operation and Tillage

	Corn Production	Soybean Production
	(kgC per hectare)	
Conventional	72.0	67.5
Reduced Tillage	45.3	40.7
No-Till	23.3	23.3

Note: Tillage definitions consistant with the Conservation Technology Information Center (CTIC)

According to the ARMS, the range in quantity of energy used to produce corn can vary significantly. In dollar terms, the survey found that efficient (low-cost), generally large producers use one-third the energy that smaller producers use on a per-planted-area basis. On a per-bushel basis, "low-cost" producers use less than one-fifth the energy high-cost producers use. Low-cost corn farms used less than half the energy that the average corn farm used on a per-bushel basis. While the sources of this difference are not all explicitly brought out in the report, low-cost producers are significantly more likely to use no-till planting practices than high-cost producers, 23% of low-cost corn farms versus 15% of high-cost corn farms. Low-cost farms were larger on average, growing 332 acres of corn per farm compared with 137 acres of corn for high-cost farms. Beyond the differences in tillage practices, high-cost corn producers used significantly more energy to run irrigation pumps.

Table 8.3 Energy Costs Comparison of Low and High Cost U.S. Corn Farms (2001)

	Low Cost	Middle	High Cost	Average
Yield (bushels/acre)	163	146	90	144
Energy Cost ($/acre)	11.1	24.32	33.18	20.88
Energy Efficency ($/bushel)	0.07	0.17	0.37	0.15
Energy Use Relative to Low Cost		2.45	5.41	2.13

Source: USDA - ARMS Survey - Characteristics and Production Costs of U.S. Corn Farms, 2001

Emissions from Nitrogen Fertilizer and Manure Application

Several factors can affect the emission of GHGs from applied fertilizer. By far and away, the dominant GHG is nitrous oxide. Nitrogen-containing materials including nitrogen fertilizer, animal waste, decomposition of soil organic matter, and breakdown of legume crop residue, are associated with potential nitrous oxide emissions. Beyond the level of emissions from agricultural soils, an additional source of emissions can be attributed to agricultural production and the use of fertilizer that moves off the field either by water or air and ultimately releases nitrous oxide into the air.

Beyond the fact that there are several potential sources of nitrous oxide, the ultimate level of emission into the air is influenced by the interaction with the soil, climate, and their levels. For commercial fertilizer, each of the many different forms of nitrogen interact differently with the soil, climate, and crop-management practices to create different nitrous oxide emissions levels.

The sources of nitrogen applied (anhydrous ammonia, urea, and ammonium nitrate) have the potential to create substantial GHG emissions depending on their application rate, soil texture/moisture/organic matter, placement, timing, and crop uptake. The amount of nitrogen applied affects the emissions of nitrous oxide such that a moderate application rate (sufficient for relatively high yields) results in the least emissions on both an absolute level and per-unit-of-production level. At low rates of nitrogen fertilization, soil organic matter will decompose and release GHG, while at overly high application rates excess nitrogen levels (beyond that needed for crop uptake) will persist in the soil, producing increased levels of nitrous oxide. Anhydrous ammonia fertilizer has the widest variation of emission levels measured in scientific tests. The reasons for the wide variation in emissions from anhydrous ammonia are due to the product's interaction with the soil under alternative moisture, temperature, and soil organic matter levels. Reported emission levels range from .04% of applied N to nearly 7.0% of applied N. The most common measure of nitrous oxide emissions per unit of applied N is around 1.0–1.5%.

Emissions from legume-derived nitrogen can be significant. Emissions of nitrous oxide from comparable soils where a soybean/corn rotation was grown compared with a continuous corn rotation show elevated background nitrous oxide levels in the corn/soybean rotation. Similar observations have been made in soils with nitrogen-fixing tree species present.

Manure can also be a source of GHG emissions, but has a limited overall influence due to its limited geographic use. The USDA estimates show manure being used on 17% of corn, 6% of soybean, 3% of winter wheat, and 4% of cotton acreage. Depending on the manure-management practices used, the level of emissions can vary significantly.

Controlled-release nitrogen fertilizer has the potential to affect GHG emissions as they can better time the availability of nitrogen with crop needs and can lead to optimal use of applied nitrogen such that nitrogen use and emission per unit of production can be minimized.

Generally, the combination of fertilizer application rate, management practice, and production technology that results in the highest yield per unit of applied N also results in the lowest per unit GHG emissions. In the future, the release of nitrogen-efficient corn by Monsanto and possibly others could cause GHG emissions and the energy balance associated with corn to change significantly for the better.

Energy Use

At the national level the GHG emission associated with the energy used for tillage and planting of corn versus soybeans is not that different. While corn is the more energy-intensive crop, soybeans still require nearly 90% as much energy as corn under the same tillage system. In the case of no-till farming, the energy use is virtually identical.

While the tillage energy used to produce corn versus soybeans is very similar, the difference between conventional tillage and no-till corn production is huge, a three-to-one ratio. The relationship between no-till and conventional soybeans is similar, but given the otherwise low GHG emissions for soybeans, tillage energy is much more important to soybeans versus

corn. In percentage terms, tillage energy efficiency gains in soybean will have a much greater effect on the crop's total GHG emissions relative to a similar change for corn. In the case of conventional tilled soybean, emissions from tillage energy represent over half of all GHG emissions, but only 16% for corn.

Ethanol Plant Energy Feedstocks and Energy Efficiency

Ethanol plants have been fueled by a variety of feedstock sources. While natural gas is the dominant fuel source in recent plants, coal and, to a lesser extent, cellulosic materials have been used as feedstocks in some plants. Each of these types of feedstock have radically different implications for GHG emissions. Using coal as a feedstock increases ethanol's direct GHG emissions above those associated with conventional petroleum; however, using natural gas as a feedstock reduces GHG emission by over 20% compared with conventional petroleum. Utilizing wet distillers' grains and cellulosic materials offers even higher GHG emission reductions, with GHG reductions approaching or exceeding 90% (see Figure 8.4).

Energy efficiency within ethanol plants is improving, reducing GHG emissions. In a study by Christianson, dry mill ethanol plants producing dry distillers' grains reduced their BTU usage by nearly 14% over 2004–07. Dry mill ethanol plants producing wet distillers' grains reduced their BTU usage by over 21% during the 2004–07. New technology is already developed and in the commercialization phase that will further reduce the energy requirements for ethanol plants. Using a "no-cook" process where the corn is not cooked before it goes into fermentation further reduces natural gas usage by 8–15%.
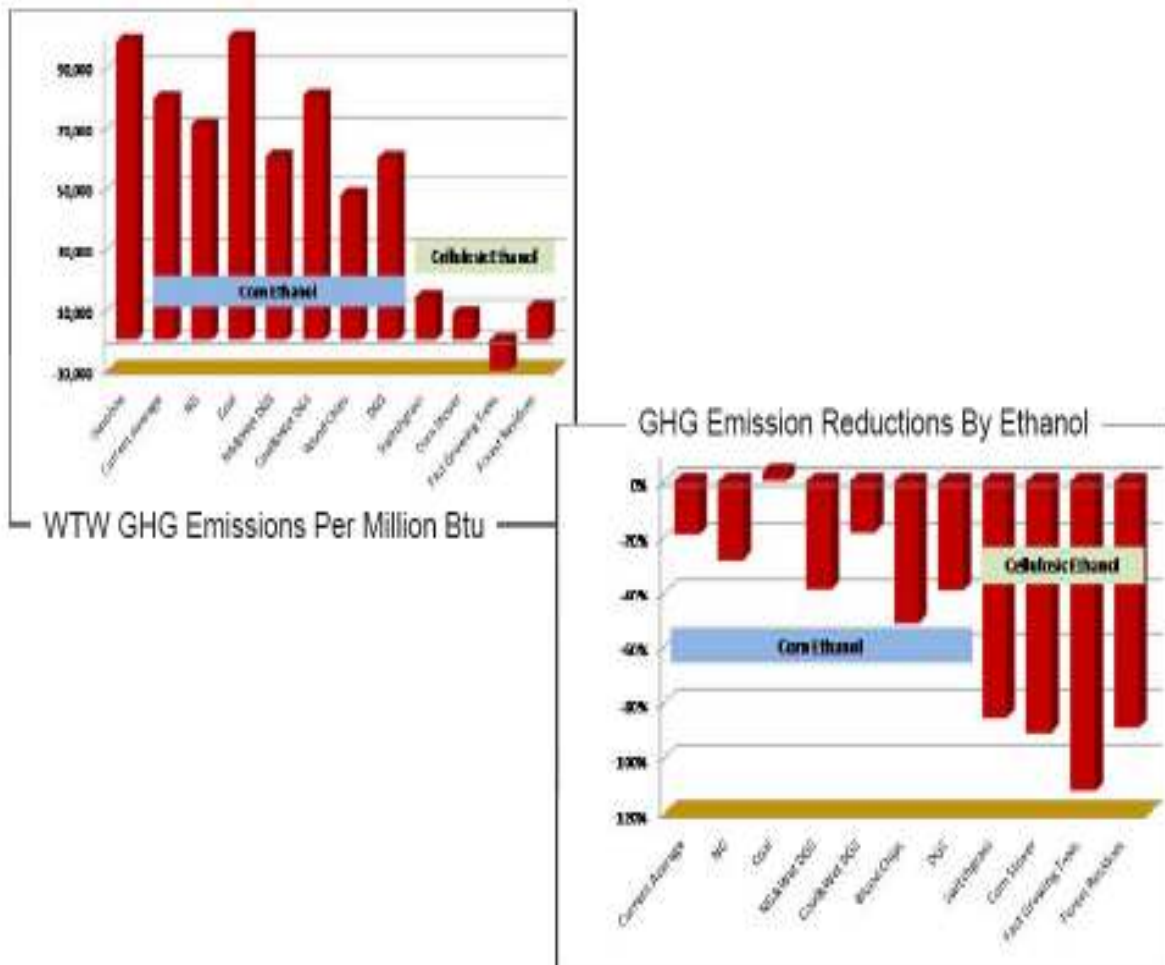
In the next two to three years, fractionation is expected to be more widely adopted by ethanol plants. Fractionation is the process in which the corn kernel is separated into endosperm, germ, and bran. The starch from the endosperm continues to go to the fermentation process for the making of ethanol and offers even higher ethanol yields with the inhibitors in the germ and bran. The germ can be processed to make food-grade corn oil as well as nutraceuticals

and food proteins. The bran can be burned in a solid fuel combustor, reducing natural gas usage by over 60%, or the fiber portion of the bran can be used as a feedstock for cellulosic ethanol production.

Ethanol Feedstocks

Figure 8.4 also illustrates the reduction in GHG emissions relative to conventional gasoline from alternative feedstocks to corn in ethanol production. Nevertheless, economically, these alternative feedstocks still struggle to compete with the profitability of corn ethanol. The closest cellulosic feedstocks to economic feasibility are the fiber created from the fractionation process and corn cobs. Other types of cellulosic materials such as corn stalks, miscanthus, and switchgrass have potential, but technologies for handling, storage, and processing still need to be improved.

Figure 8.4 GHG emissions vary significantly based on process fuels used in ethanol plants

Source: Michael Wang, "Overview of GREET Model Development at Argonne" March 18, 2008

Ethanol Yields

Denatured ethanol yields per bushel of corn continue to improve, growing from 2.795 gallons per bushel in 2004 to 2.802 gallons per bushel in corn in 2007 based on survey results reported by Christianson. In 2007, the average denatured ethanol yields among the leading plants were 2.871 gallons per bushel. This level is significantly different than the 2.65–2.72 gallons per bushel assumed in the GREET model. In addition, technology is in the pipeline to further increase ethanol yields per bushel, with yields approaching 3.0–3.1 gallons per bushel in the next 10 years, with a yield potential of 3.3 gallons per bushel.

New Ethanol By-Products

With fractionation, food-grade corn oil and food proteins will emerge as new, high-value by-products. The production of food-grade corn oil can help ease pressure on vegetable oil prices, as well as further reduce GHG emissions. Other technologies are also available to remove low-quality corn oil from distillers' grains for use as a feedstock in the biodiesel industry.

IX. INDIRECT GHG EMISSIONS ASSOCIATED WITH BIOFUELS PRODUCTION

It has been argued that an analysis that only accounts for the net GHG emissions as described above is incomplete, because it ignores an indirect effect of using corn for ethanol. The use of large amounts of corn for fuel production reduces the amount of corn available for other uses, such as animal feed and food uses. In the current supply/demand situation, the increase in corn demand relative to the supply has led to a large increase in corn prices. This led to an increase in acreage planted to corn, which led to a decrease in acreage planted to other crops, most notably soybeans, which had been in ample supply. This in turn led to an increase in soybean prices. Other crops, such as cotton, experienced a decrease in planted acreage due to higher corn prices, but cotton prices did not rise dramatically because U.S. cotton supplies have been dramatically higher than demand in recent years.

If most crops were in the same supply/demand situation as U.S. cotton, then the diversion of large amounts of corn to new uses would not be viewed as a significant issue. Supplies of many crops are relatively tight globally, however, and world prices of most major crops are at high levels. This has triggered concern that biofuel-induced crop "shortages" and resultant high prices will lead to an increase in global acreage planted with crops. In many ways, increased crop demand, higher crop prices, and more acreage could be viewed as a good thing, especially in less-developed countries where farmers have struggled to make a living.

The increase in acreage creates problems in terms of GHG emissions, however, if the increase in acreage comes as the result of clearing land that had been undisturbed, such as forests and grasslands. Such lands, especially forests, have stored large amounts of carbon in the vegetation as well as in the soil. The clearing of these lands for agricultural use results in releasing this previously stored carbon into the atmosphere, potentially in amounts far larger than can be sequestered by the subsequent production of crops. The actual amount of carbon released depends on many factors, such as the density of the vegetation, the type of

vegetation, the type of soil, and the method of clearing used. If trees are cut for timber, for example, the carbon release would be less than if the forest was simply burned. It also can be argued that from a long-term GHG standpoint, clearing relatively young forests, in which trees are still storing carbon each year, is worse than clearing older-growth forests, in which the trees are not growing and storing much carbon.

The importance of accounting for potential indirect effects associated with the production of biofuels was reinforced with the passage of the Energy Independence and Security Act (EISA) of 2007. Among its many provisions, EISA requires LCA to be performed that includes indirect effects such as clearing of new lands for crop production, either in the United States or elsewhere in the world. The EPA is charged with quantifying these indirect effects. Ultimately, going forward, the EISA requires biofuels to show significant reductions in GHG emissions relative to gasoline. Corn-based ethanol from new production facilities must show a 20% reduction in GHG emissions relative to gasoline, while most other new biofuels must show a 50% reduction.

Recent Analyses of GHG Emissions from Land-Use Changes

The need for LCA to include such indirect effects has been recognized for a while, but prior to 2008 few studies made much attempt to rigorously examine the issue and quantify the effects. Two articles that were published in *Science* magazine in early 2008 received a great deal of public attention because they imply that widespread adoption of biofuels, especially the types of biofuels used currently, will produce more GHG emissions than conventional petroleum-based gasoline due to indirect land-use changes.

The study by attorney Timothy Searchinger et al. states that production of corn-based ethanol "instead of producing a 20% savings, nearly doubles GHG emissions over 30 years and increases greenhouse gases for 167 years." The article states that the projected increase in U.S. biofuel production would lead to the clearing of 10.8 million hectares of land

for additional crop production. The carbon initially released into the atmosphere by this land clearing would be offset over time by the carbon removed from the atmosphere by the production of crops for biofuels, but it would take 167 years for the carbon "debt" to be repaid. The other study, by Fargione et al., looks at the carbon debt associated with the conversion of various types of land to agricultural production.

Both studies have generated much attention, including headlines in many major news outlets. The studies have also generated comments, both pro and con, from researchers in the field. The Searchinger study, which features the more comprehensive attempt to quantify the total impact of biofuels, has generated a flurry of comments and rebuttals. The study does have some shortfalls, partly due to flawed assumptions and due to lack of adequate data upon which to base sweeping conclusions, especially conclusions with major policy implications.

Shortcomings of Land-Use Change Analyses

One feature of the Searchinger et al. study that stands out is that it models an extremely high level of corn-based ethanol production, and therefore a large increase in corn usage. As Michael Wang of the Argonne National Lab points out in a letter to *Science*, Searchinger considered a case in which annual U.S. production of corn-based ethanol increases to 30 billion gallons by 2015. The authors argue that ethanol production could reach that level if crude oil prices remain at high levels, but that is double the level of ethanol production specified in the EISA.

The Searchinger et al. study further argues that their results are not very sensitive to the level of ethanol production assumed, but the underlying agricultural modeling probably does not adequately account for all of the dynamic effects created by such a large increase in corn demand and prices. Higher prices of corn and crops that compete with corn for acreage

would encourage technological advances to increase yields. Higher prices of that magnitude would also lead to major reductions in usage of corn for other purposes.
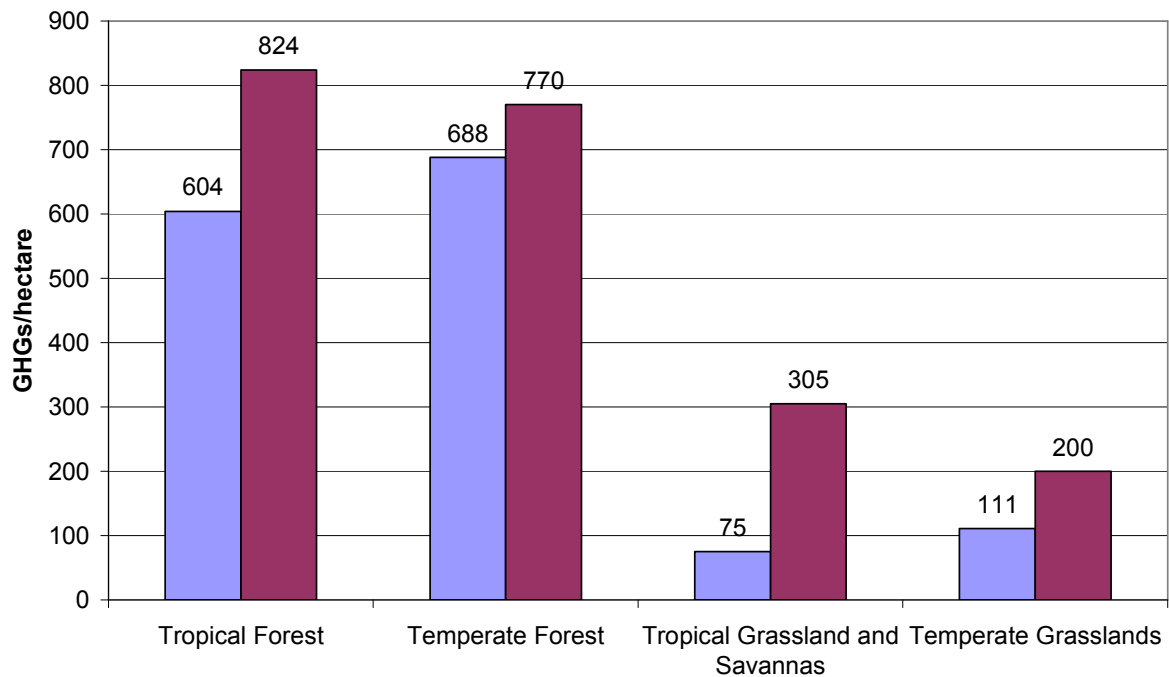
Searchinger et al. also used a number for the "payback period" for GHG emissions that is based on current technology and practices. Any analysis that purports to project GHG emissions needs to incorporate possible changes in industry practices, such as selling distillers' grains to nearby livestock farms to avoid drying and switching to cleaner sources of electricity.

This use raises a far larger point that pervades much of the discussion. Most analyses of future GHG emissions from ethanol or other fuels assume that crops and ethanol will continue to be produced pretty much the way they are now. Any judgment based upon GHG emissions needs to consider the fact that farmers, ethanol producers, consumers, and any other relevant actors have not had to consider GHG effects in the past. If new policies are put into place that provide strong economic incentives to reduce carbon emissions, then it is most likely that practices will change.

Another example of this issue is the question of where land will be converted to cropland and what types of land will that conversion entail. The agricultural model used by Searchinger et al. determined that 10.8 million hectares of new land would be brought into cultivation by the end of the analysis period, and also provided a by-country distribution of the land conversion. Each country, of course, has various types of land that could be converted, such as rain forests and *Cerrado* grassland in Brazil, and various types of forests and grasslands in the United States.

The type of land cleared can have a major influence on any analysis of GHG emissions. To illustrate, the study offers the following ranges of GHG emissions per hectare, on a carbon dioxide equivalent.

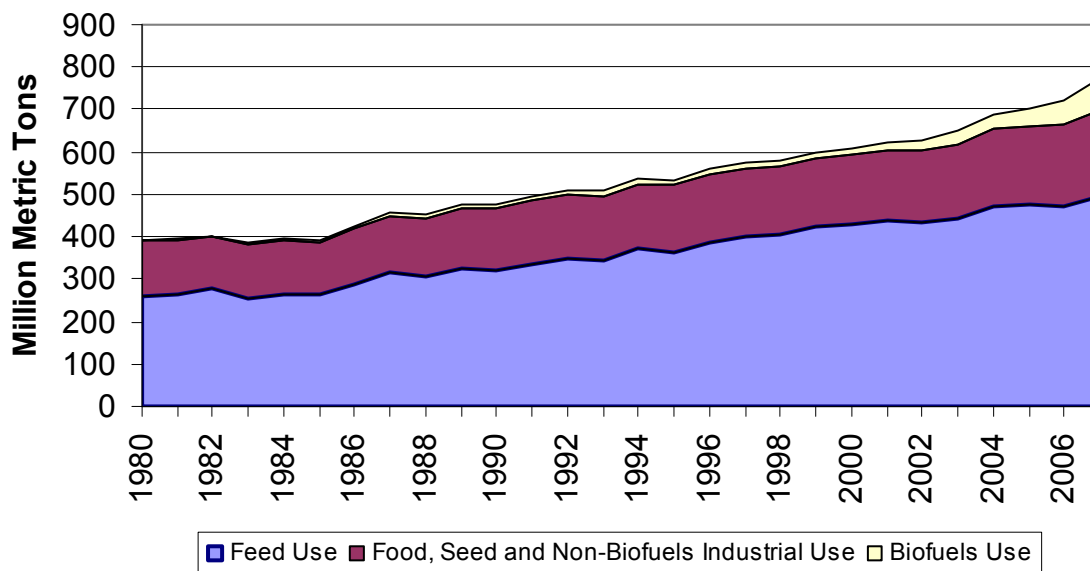## Figure 9.1 Range of GHG Losses by Ecosystem Type

On average, the greenhouse emissions ascribed to the loss of forest is over four times the emissions from the loss of grasslands in a similar climate. Therefore, the type of land cleared can have a major effect on the amount of carbon emissions attributed to expanded agricultural activities.

The study based its projection of future land-use changes on estimates of land-use changes that occurred in the 1990s. For example, if the land cleared for cropping in the 1990s was 75% forest and 25% grassland, then any new lands are assumed to be 75% forest and 25% grassland. Based on the information provided, it is not clear that their assumptions of land-use changes in the 1990s are all that accurate, based on lack of available data. For Brazil, the authors' first assumption is that new agricultural land came from rain forest; if the increase in cropped land in a given year is higher than the amount of deforestation thought to have occurred that year, then the rest is attributed to grassland.

Other Sources of Land-Use Change

Land-use changes are not new nor are biofuels the primarily driver. The demand for additional land resources has always expanded with global population growth. In the early 1800s, doomsayers called for population growth to outpace the ability of the world to supply food. Yet, the undiscovered production potential of the United States and the remarkable productivity growth of the 1900s kept supply well ahead of demand. Figure 9.2 illustrates the growth in demand for corn from food, feed, and biofuels. Even with the dramatic growth in biofuels over the last five years, the growth in corn demanded for food and feed use still exceeds the growth in biofuels. The picture is much the same for vegetable oils. Over the 2002–07 marketing period, 58% of the growth in vegetable oil demand came from food use.
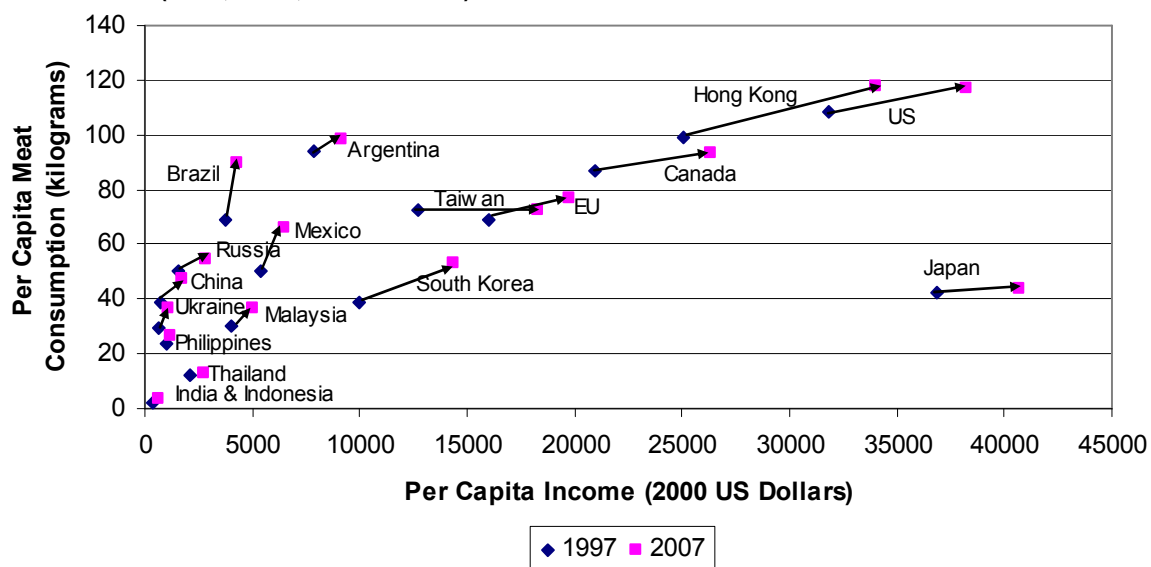
Figure 9.2 World Corn Utilization

Since the mid-1980s, demand for feed grains and vegetable oils has been growing at a faster pace. Income growth in the developing world is driving much of this increase in demand. In developing countries, consumers utilize a greater portion of their income for food. As incomes grow, consumers in developing countries seek to diversify their diet from basic staples such as rice to include more protein, particularly meat and vegetable oils. Figure 9.3 illustrates how per capita meat consumption has responded to per capita income growth in

various countries from 1997 to 2007. In the developing countries with incomes below US$10,000, meat consumption is much more sensitive to income changes than in countries where per capita incomes are much higher. Real per capita income growth exceeds 5% in many of these developing countries, driving additional meat consumption and, subsequently, the demand for more feed grains to feed the livestock. The situation is very similar for vegetable oils.

Figure 9.3 Meat Consumption and Income
(Beef, Pork, and Broilers)

The remarkable growth in food and feed demand has been supplied through growth in productivity as well as growth in land area. Figure 9.4 illustrates the total major crop area in Brazil. One can see the growth in total cropped area from 2000 through 2004. Yet, even as the biofuels boom began, Brazilian cropped area declined as weak commodity prices combined with increasing input costs and pressures from Asian rust disease created a significant crisis for the rural sector in Brazil, resulting in a decline in major field crop area in 2005 and 2006. Global Insight expects that total crop area in Brazil will resume its expansion path as strong commodity prices and infrastructure improvement stimulate additional

acreage expansion. Much of the new land that will be brought into production will likely come from the *Cerrado* areas.

Unlike in Brazil, as Figure 9.5 illustrates, Argentina's crop area has continued to expand, approaching 30 million hectares in 2007. Argentinean crop area continues to expand through the conversion of pasture lands to cropping. This area is limited, though, and Argentina's crop area expansion is expected to slow in the future. Argentina has had a long history of crop area expansion, with much of the increased production going to export markets to supply food and feed demands worldwide.

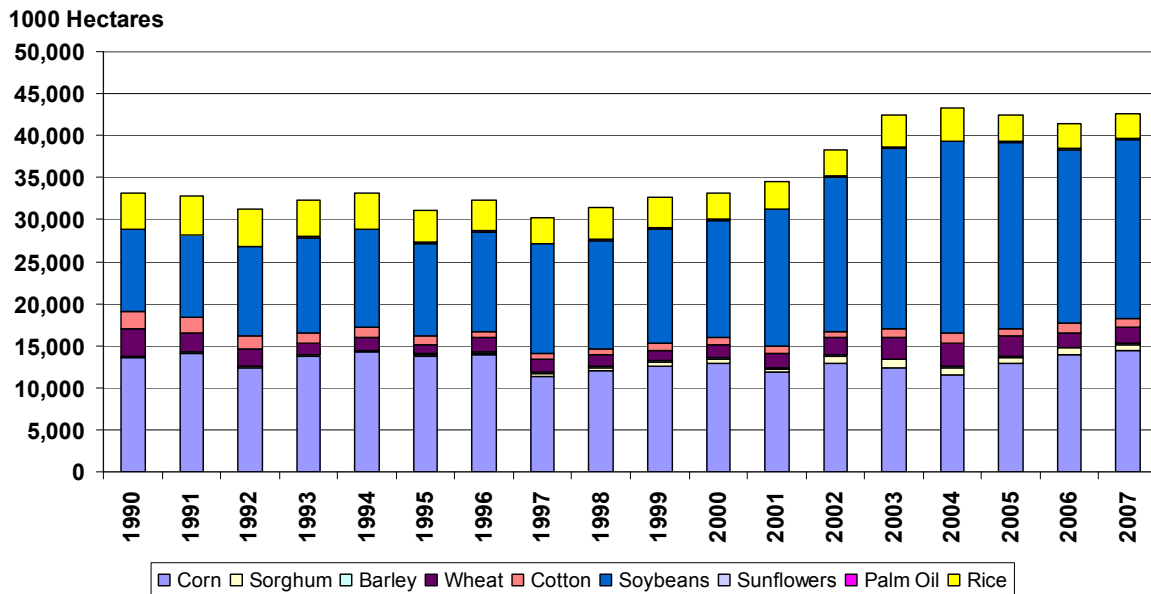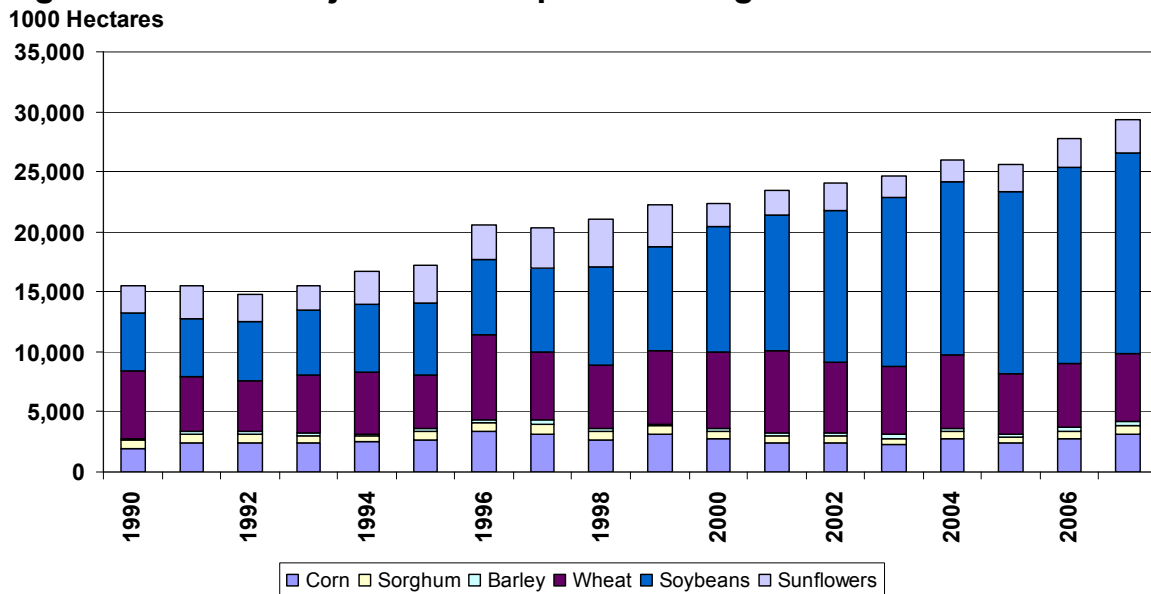**Figure 9.4 Total Major Field Crop Area in Brazil**

1000 Hectares

Corn ☐ Sorghum ☐ Barley ■ Wheat ☐ Cotton ■ Soybeans ☐ Sunflowers ■ Palm Oil ☐ Rice

Figure 9.5 Total Major Field Crop Area in Argentina

1000 Hectares

Legend: ■ Corn □ Sorghum □ Barley ■ Wheat ■ Soybeans □ Sunflowers

Just as crop area is expanding in some countries, other countries such as China have experienced declining crop area. Whether due to urban sprawl, water constraints, or changes in multi-cropping patterns, land-use change is resulting in less land being available for agriculture. Adding to the complexity of land-use change analysis, if one is to account for increases in land use, one should also consider decreases in land use as well.

Figure 9.6 Total Major Field Crop Area in China

1000 Hectares

Legend: ■ Corn ■ Corn Silage □ Sorghum □ Barley ■ Wheat ■ Cotton ■ Soybeans □ Sunflowers ■ Rapeseed ■ Palm Oil □ Rice
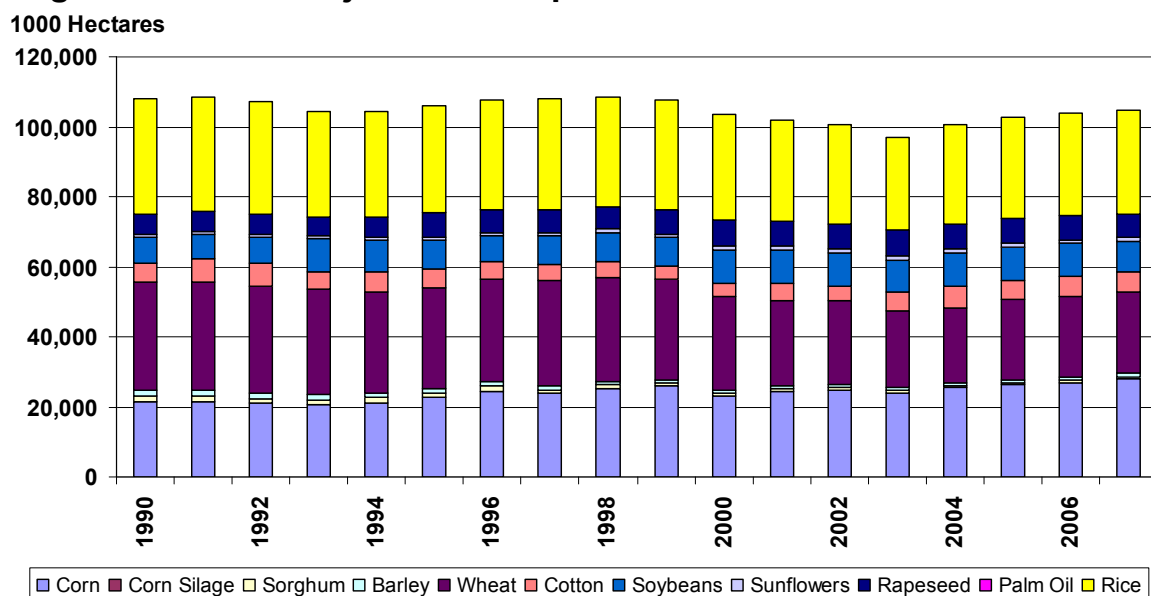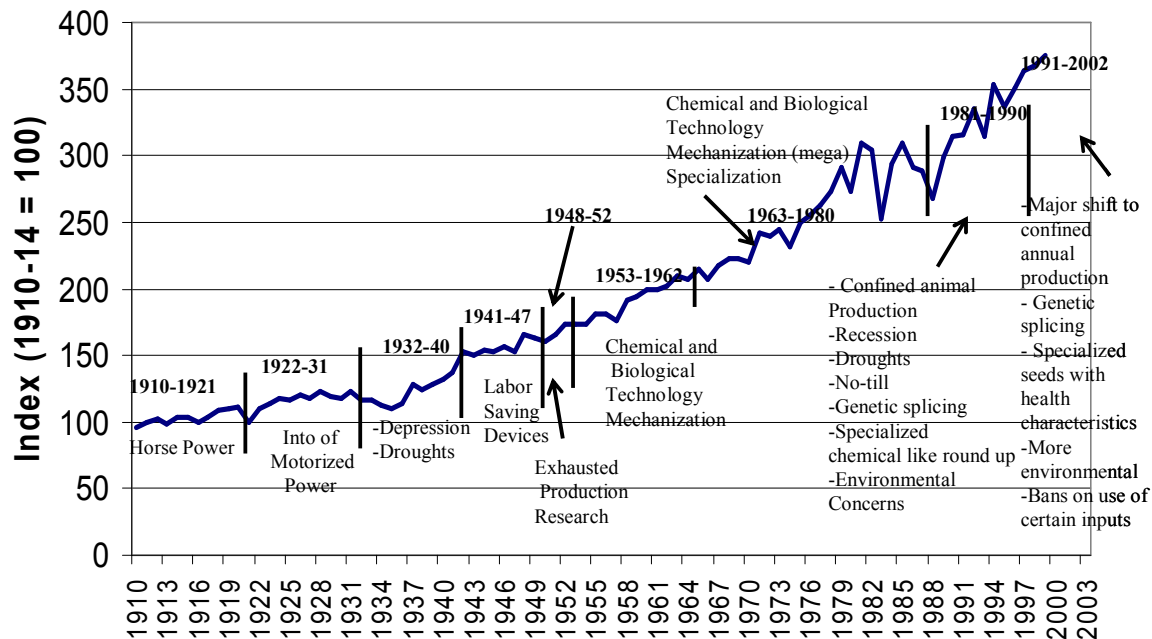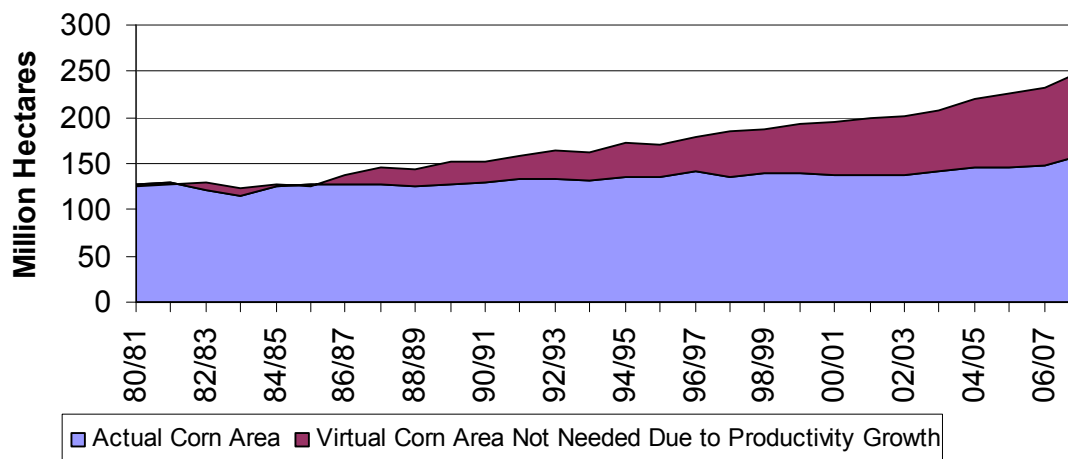
Figure 9.7 Productivity of US Agriculture

Source: Adapted from slides by Abner Womack, FAPRI

Finally, it is important to note that increases in food, feed, and biofuels use have not just been met by increases in cropped area. Productivity has changed dramatically over the past century. As Figure 9.7 illustrates, productivity in agriculture has increased nearly 400% in the last century. The combination of genetics, management techniques, inputs, and resource availability have combined to formulate the most productive growth period in agriculture in recorded history.

Another way to consider how productivity growth contributes to reducing the need for new cropped acreage is to look at the area required if no yield growth had occurred. Figure 9.8 illustrates the number of corn acres that would have been needed to meet demand if yields remained at 1980 levels. In the short span of 17 years, nearly double the number of corn hectares would have been needed if not for productivity growth.

Figure 9.8 World Corn Acres Needed
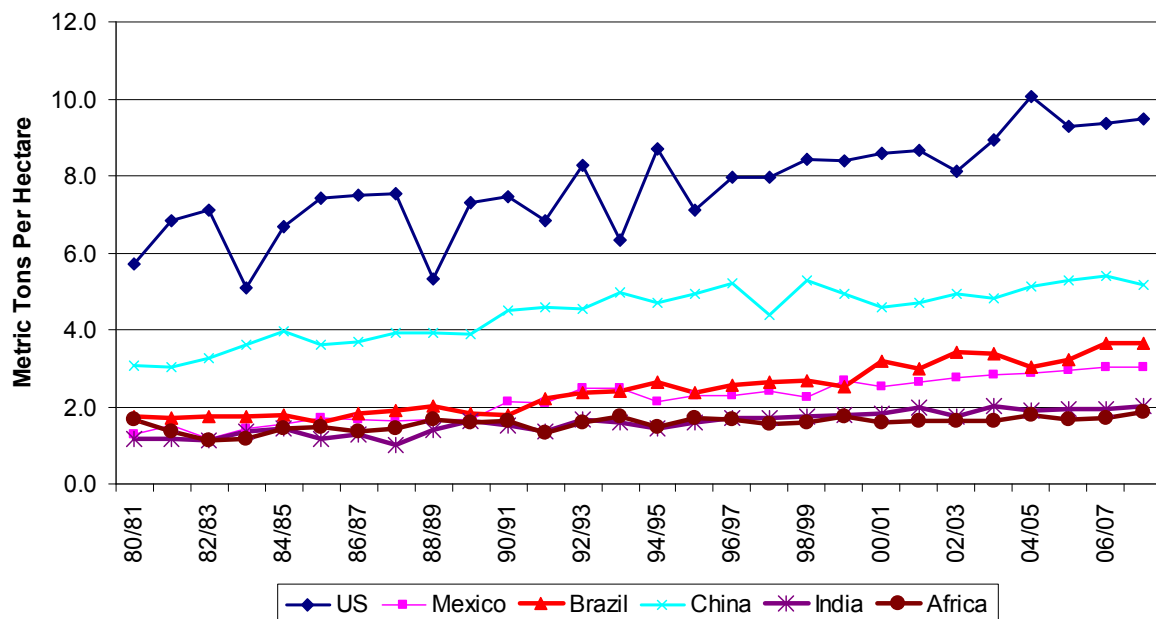## Without Productivity Growth

Investment and Commodity Prices in Developing Countries

For years, advocates of the developing countries have argued that rich countries like the United States, the European Union, Canada, and Argentina pressured world commodity prices lower by providing substantial subsidies to their agricultural sectors. Per Pinstrup-Andersen with the International Food Policy Research Institute (IFPRI) argued in an April 2008 article that international cotton and oilseed prices would increase 21% and 15%, respectively, with full trade liberalization and removal of subsidies. Developing countries have long argued in World Trade Organization (WTO) negotiations that low global commodity prices provide no incentive to their unsubsidized agricultural producers to produce more, and they discourage investment, contributing to expanding poverty and hunger in their countries. Since September 2006, agricultural commodity prices have risen sharply, with corn up 155%, soybeans up 172%, wheat up 80%, and rice up 85%. This increase in agricultural prices has heightened interest in investment in agriculture in the

developing regions of the world. At the July 2008 Inter-American Institute for Cooperation on Agriculture (IICA) conference, the experts agreed that rising commodity prices should be looked at as an opportunity for agriculture in the Americas, with the expectation of additional investment in the sector.

Investment in agriculture in developing countries will need to come in a variety of forms including investment in rural infrastructure, farm management, land and property rights, and yield-increasing technologies. Higher commodity prices incentivize developing-country producers as well as encourage their governments to invest in local food production to reduce dependence on food imports. A simple comparison of commodity yields in developing nations suggests there is a lot of opportunity for improving productivity, especially given gains in U.S. corn yields in recent years (see Figure 9.9).

Figure 9.9 Corn Yields in Selected Countries

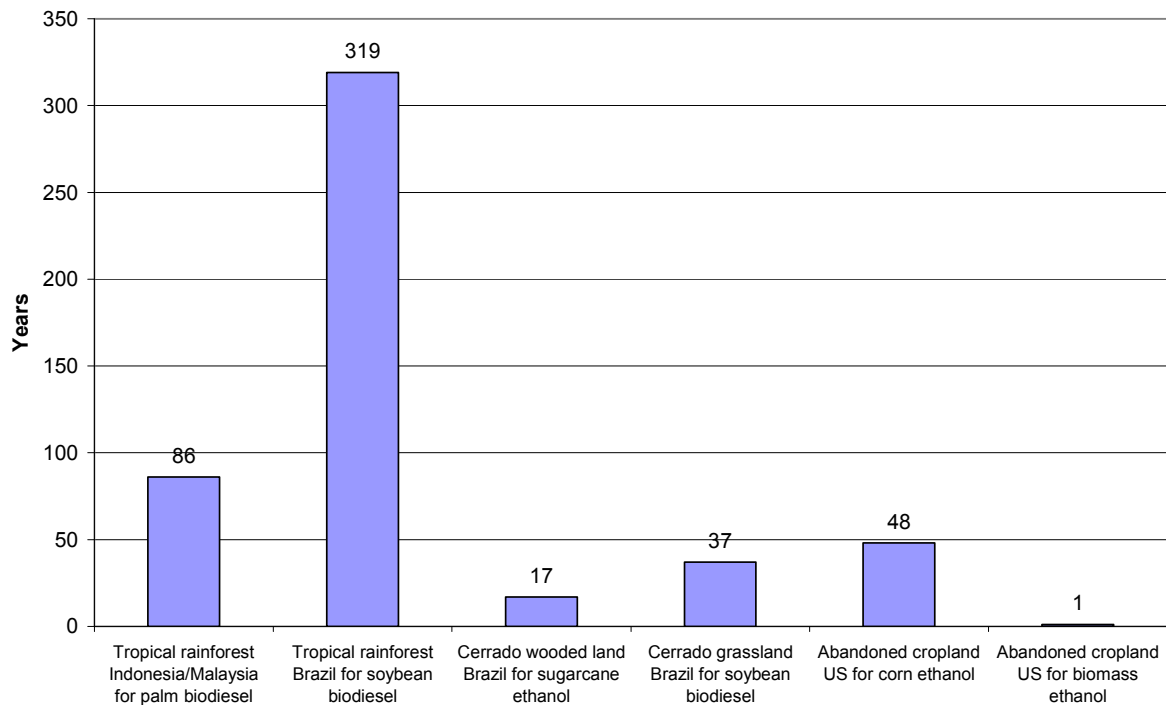

Potential Policy to Influence Land-Use Change

Even if the data on land-use changes are assumed to be reasonably accurate, Searchinger and Fargione make no argument in favor of their assumption that future land-use changes will follow the pattern of the recent past. At least some recent studies indicate that the rate of deforestation in Brazil declined in the early 2000s relative to the previous two decades. The issue of Amazonian rain forest clearing has gradually captured the world's attention in the past 30 or so years, but only fairly recently have policies been implemented (and more importantly, enforced) to reduce deforestation. The rate of deforestation in the 1990s may have even been accelerated in anticipation of more stringent policies.

Considering the potential costs and rewards associated with efforts to reduce carbon emissions from transportation fuels and other sources, it seems likely that many policies will, or certainly could, be implemented to address potential unintended consequences of increased biofuel production. The European Union has already seen an effort to assure that

its program to increase production of biofuel does not promote deforestation in the Amazon. So far, the effort seems rather incomplete, in that it mainly requires imported soybeans or soybean oil to come from already-established farmland. This still ignores displacement effects, but illustrates the type of program that can be implemented. A large-scale, multinational carbon trading program will generate plenty of money that could be used to fund programs to stave off deforestation and direct the establishment of any new farmland to more environmentally desirable areas.

The study by Fargione et al. in *Science* helps to illustrate the potential benefits of using policy instruments to guide land-use changes in order to mitigate potential GHG emissions. The authors estimate the number of years it would take to repay the carbon debt associated with conversion of various ecosystems to production of feedstocks for biofuels. The estimated carbon debt associated with the land conversion is divided by the estimated annual repayment achieved via carbon sequestration of the crop. As illustrated below, the conversion of some types of land would be disadvantageous, while other combinations would have a much more benign GHG impact. Rather than dismiss biofuels as generally "bad," policies could focus on the desired types of land conversion.

Figure 9.10 Estimated Time to Repay Carbon Debt

The governments in some of the countries that would potentially see the biggest increases in land conversion may also have other reasons to implement policies. In Brazil, for example, researchers are investigating whether rain forest clearing in the Amazon is contributing to localized droughts. If deforestation in Brazil can potentially cause drought within Brazil, then the Brazilian government would have some reason to act on its own, rather than waiting for incentive money from wealthier countries.

Data Impediments to Valid Land-Use Change Assessment

The increased use of biofuels could certainly lead to unintended consequences such as the clearing of land to make up for the volume of crops being used as a feedstock for fuels, and the issue does warrant further study. Nevertheless, as pointed out in a letter recently signed by dozens of scientists involved in the issue of alternative energy, sound policy decisions

need to be based on solid empirical evidence utilizing reliable data and models created specifically to incorporate the relevant issues.

For now, the issue of indirect land use certainly appears to lack some of the data necessary to conduct robust analyses. Revisions to estimates published by the UN Food and Agricultural Organization (FAO) point out some of the data issues moving forward. As reported by a researcher with the Woods Hole Research Center (also one of the co-authors of the Searchinger paper on land-use change), FAO's Forest Resources Assessment for the year 2000, published in 2001, reported that the annual rate of loss of natural forests in the tropics averaged 16.7 million hectares annually during the 1990s. In the 2005 assessment, published in 2006, the rate of forest loss in the tropics during the 1990s was lowered to 11.6 million hectares, a decrease of 30%.

Searchinger et al. refers to an article by Douglas Morton et al. published in September 2006 in the Proceedings of the National Academy of Sciences of the United States of America as proof of deforestation in Brazil for cropland production. The methods discussed by Morton and others utilize satellite images to identify changes in forest area in Brazil. While utilization of satellite images is a significant breakthrough in technology, Morton notes "misclassification" problems from attributing deforestation with pasture versus fallow agricultural cycles or single-crop rotations. Morton validates his study by comparing field observations with the land categorizations derived from a decision tree classifier that utilizes the satellite imagery data. His results indicate that the number of observations used to validate "forest" data and "not in production" data were 5 and 11, respectively, a very low level of observations for any statistical tests. Of particular concern is the amount of error associated with identifying the areas not in production as cropland areas. Of the 11 observations, 6 were identified as cropland, when in fact, they were not in production for a 54.55% error. This level of error suggests that the model could overstate the amount of deforestation associated with cropland.

Searchinger et al. also refers to the article by Morton et al., stating that, "Studies have confirmed that higher soybean prices accelerate clearing of Brazilian rainforest." They do not note that only one-third of the cropland area expansion in Mato Grosso was attributable to deforestation by the study. In addition, they also fail to mention that Morton et al. estimated the relationship between land deforested for cropland and soybean prices based on only four years of data over 2001–04. Finally, using the maximum estimate in the range of forest converted to cropland in the Morton et al. study, only 14.3% of the estimated total area deforested in Mato Grosso, Brazil was converted to cropland over 2001–04. The Morton et al. article attributes less than one-third of the total cropland expansion in Mato Grosso over the 2001–04 period to deforestation after adjusting for double-cropping, with the remaining two-thirds of the cropland expansion roughly split evenly between Cerrado and pastureland.

Even if data become available on land-use issues, another major data issue is exactly how much carbon release occurs when land is cleared. The study of carbon "flux" appears to feature a good deal of empirical uncertainty, as illustrated by the following passage from Goward, et al., (2008):
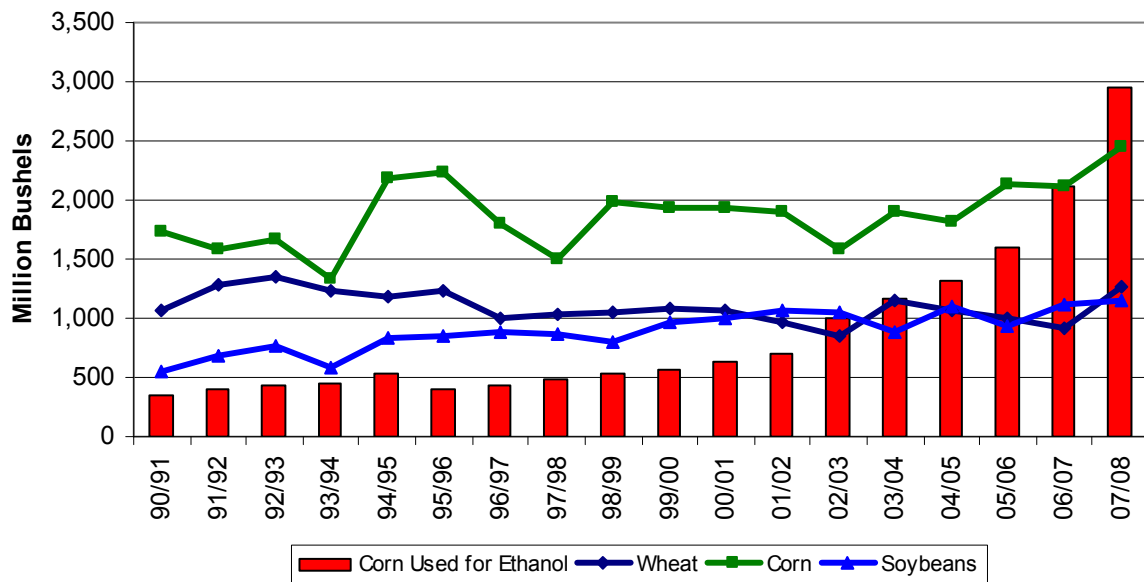
> North America's forests are thought to be a significant sink for atmospheric carbon. Currently, the rate of sequestration by forests on the continent has been estimated at 0.23 petagrams of carbon per year, though ***the uncertainty about this estimate is nearly 50%.*** (Emphasis added)

Even if that estimate of uncertainty is abnormally high for the field of study, it certainly illustrates the potential problems inherent in a rush to quantify the potential GHG effects of land-use change. Alex Farrell with the Energy and Resources Group, University of California – Berkeley summed up this issue well in his presentation comment in March 2008, "The size of GHG emissions from indirect LUC [land-use change] is poorly understood – 1 data point so far (Searchinger et al 2008)", suggesting that there was only one estimate of indirect LUC impacts provided by attorney Timothy Searchinger and that more research was needed.

The CARD-FAPRI Model

Searchinger references the CARD study entitled, "Emerging Biofuels Outlook of Effects on U.S. Grain, Oilseed and Livestock Markets." Based on the comparisons made by Searchinger and his references, it appears that he is using CARD's high oil price scenario as the basis for creating his land-use change calculations. The CARD analysis states that "[U.S.] corn, soybean, and wheat exports would decline dramatically if high crude oil prices greatly stimulated U.S. ethanol production." Table 2 of the report shows corn exports declining 62% as a result of high crude oil prices; however, the experience of 2007/08 has near-record corn exports at the same time as record corn used for ethanol and record highs for crude oil prices (see Figure 9.11).
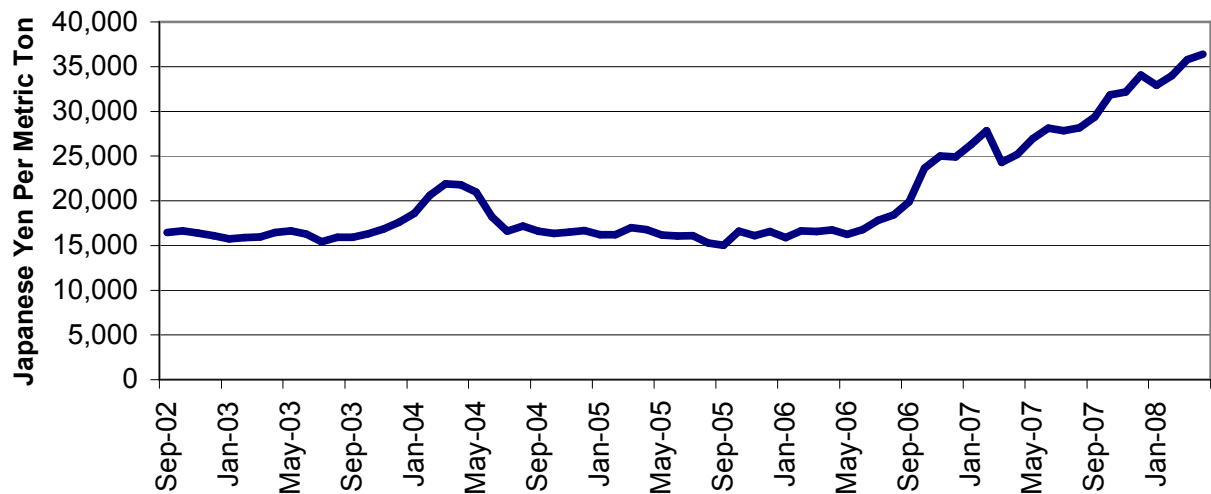
Figure 9.11 U.S. Wheat, Corn, and Soybean Exports
Marketing Year Basis

Some have attributed this surge in U.S. corn exports to the weak value of the U.S. dollar, but the increase in shipping rates has more than offset the value of the weaker dollar. Figure 9.12 illustrates the total cost of corn including shipping to Japan via the Gulf of Mexico

multiplied by the exchange rate. Clearly, the weakening of the dollar has been offset by the increase in transportation costs.

Figure 9.12 Landed Cost of Corn in Japan

The actual experience of 2007/08 when compared with the simulation results of the CARD international econometric models suggests that either the international supply elasticities are likely too large, the international demand elasticities are too large, or that the short-run supply elasticities are much smaller than the long-run elasticities. Since U.S. exports did not decline despite high prices, it suggests that the international acreage response at least in the short run was relatively small, explaining why U.S. exports did not decline. Economic theory suggests that the longer-run responsiveness will be larger, but U.S. exports may still remain close to historical averages depending on how much the international sector responds. (The CARD report does discuss their short-run versus long-run international supply elasticities.) On the international demand side, it is surprising that despite record-high commodity prices, demand did not back off more. It could be that even the relatively inelastic food and feed demand elasticities in the CARD model are still too large since demand did not respond to high commodity prices as much as expected. (Searchinger et al. state in the article that

"farmers will replace most of the grain diverted from food and feed by ethanol because the demand for overall food and feed[—]as opposed to any particular grain[—]is inelastic." This suggests that the demand elasticities in the CARD model are not too large, but the elasticities are not reported.) If the supply elasticities in the CARD model are too large, then the 2007/08 experience may imply that the international land-use changes tend to be overstated in the CARD analysis. The CARD models should be made publicly available for peer review of the equations, elasticities, and historical dynamic simulation statistics to determine if it is an appropriate tool for assessing land-use changes.

The CARD report states that it is using trend yields with the exception of its drought scenarios. Based on its graphs, it appears that its trend yields are a little low by historical standards, but trend yield estimates are sensitive to the period of estimation. The importance of global productivity growth should not be understated in simulating land-use changes. Despite the 93.6 million acres of corn planted in the United States in 2007, yields were still one bushel per acre higher than in 2006/07, even with a significant drought in the southeastern United States. This is directly contrary to the second caveat mentioned on page 26 of the report that states, "One would think that increased corn plantings would begin to cause corn yields to decline because the additional corn acreage would not be planted as much in rotation with soybeans and it would be planted on increasingly marginal (lower-yielding) land outside of the Corn Belt." Regional analysis of 2007 production data suggests that corn acreage increased in some of the most productive areas of the United States, i.e. Iowa, Illinois, Indiana, and Ohio, resulting in high corn yields despite higher acreage.

Another factor often ignored in trend yield analysis is that productivity growth also tends to accelerate in periods of high prices because new technologies are more affordable and more quickly adopted by farmers. Adoption of new technologies is quick because farmers are incentivized to increase their yields to take advantage of high commodity prices. In addition, seed companies often increase seed prices during periods of high commodity prices,

providing more funds for investment in new technologies. (As recent evidence, in July 2008, Monsanto has indicated to its customers that it will raise seed prices for corn and soybeans in 2009.) For this reason, both corn and soybean yield growth will likely accelerate over the next several years. Monsanto and DuPont have announced several new technologies including:

- Eight-way trait stacking
- Roundup Ready 2™
- New soybean varieties
- Drought tolerance
- 40-60% better nitrogen utilization in corn

Monsanto and DuPont have increasingly discussed their expectation of a 10% step in crop yields that would begin in 2009 with the release of Roundup Ready 2™ technology for soybeans and the eight-way trait stacking for corn. The step in yield might not all occur in the first year since not all farmers will adopt the technology immediately, but with current commodity prices the adoption is expected to occur much more quickly.

As the EPA considers the technology assumptions with regard to yields, it should consult with the genetics companies such as Monsanto and DuPont to understand the technologies already in the pipeline. These technologies are not only directed at enhancing productivity, but also help reduce GHG emissions through technologies that encourage better utilization of inputs, such are reducing nitrogen fertilizer requirements for corn. The technology assumptions should be reflected in the CARD models.

X.   INDIRECT GHG EMISSIONS AND PETROLEUM

The previous chapters of this report have focused on the LCA methodologies used to calculate the direct and indirect costs of producing ethanol, particularly corn ethanol. The EPA compares the LCA of biofuels with the 2005 LCA for petroleum. While the nebulous indirect GHG emissions associated with producing corn ethanol have been highlighted by the EPA, no directive has been given to the EPA, nor does there appear to be any research by the EPA, on the indirect GHG emissions associated with petroleum production. Yet, several research centers, including the Congressional Research Service, Securing America's Future Energy, and the International Center for Technology Assessment (CTA), have noted the indirect military costs associated with securing petroleum from foreign sources. The Congressional Research Service performed a literature review on the indirect military costs in 1992 and found estimates ranging from US$56 billion to US$73 billion. Unfortunately, the review did not include an estimate of GHG emissions associated with these expenditures. The research center Securing America's Future Energy specifically notes military costs and risks. It states, "the need to secure global oil supplies requires substantial defense expenditures and involves significant risks to American forces—none of which are factored into the market price of oil." They cite four examples of the use of U.S. troops to protect foreign oil sources including CENTCOM, which ensures "unfettered access" to Middle East oil supplies; SOUTHCOM, which defends Colombia's Cano Limon pipeline; EUCOM, which trains local soldiers to guard the Baku-Tbilisi-Ceyhan pipeline in West Africa; and PACOM, which protects tanker routes in the Indian Ocean, the South China Sea, and the Western Pacific. The CTA reviewed gasoline cost externalities in January 2005, concluding that the cost for security and protective services for petroleum ranges from US$78.2 billion to $158.4 billion or approximately US$0.21-0.32 per gallon of gasoline. The CTA also notes, "the full military costs of defending petroleum resources are difficult to estimate due to the complex

nature of global security and the synergy between energy supplies and economic security."

Mark Delucchi and James Murphy estimated the cost of defending U.S. interests in the

Persian Gulf at between US$47 billion and US$97.8 billion for 2004. These studies all

suggest that there are indirect costs associated with the military to protect petroleum

supplies. Incurring these costs also generates GHG emissions, particularly from the use of

petroleum in military vehicles. These indirect GHG emissions are not included LCA for

petroleum but should be accounted for if indirect LUC is included for corn ethanol LCA.

XI. IDENTIFYING THE MARGINAL IMPACT OF BIOFUELS VERSUS THE MARGINAL IMPACT OF NEW SOURCES OF OIL PRODUCTION

The EPA compares all GHG emissions from alternative fuels with GHG emissions associated with conventional petroleum sources. Nevertheless, high oil prices have incentivized the production of crude oil from other sources such as tar sands and coal, which have considerably higher GHG emissions. (Figure 11.1 shows that heavy oil sources, i.e. Canadian tar sands, cost between US$40 and US$75 per barrel to mine, well below current oil price levels. Other sources indicate these costs may be as low as US$30 per barrel for specific situations.) Depending on the energy source used in the mining of tar sands, well-to-pump GHG emissions can be over 300% of conventional crude oil, as demonstrated by the GREET model (see Figure 11.2).

Figure 11.1 Cost of Producing Oil From Various Sources

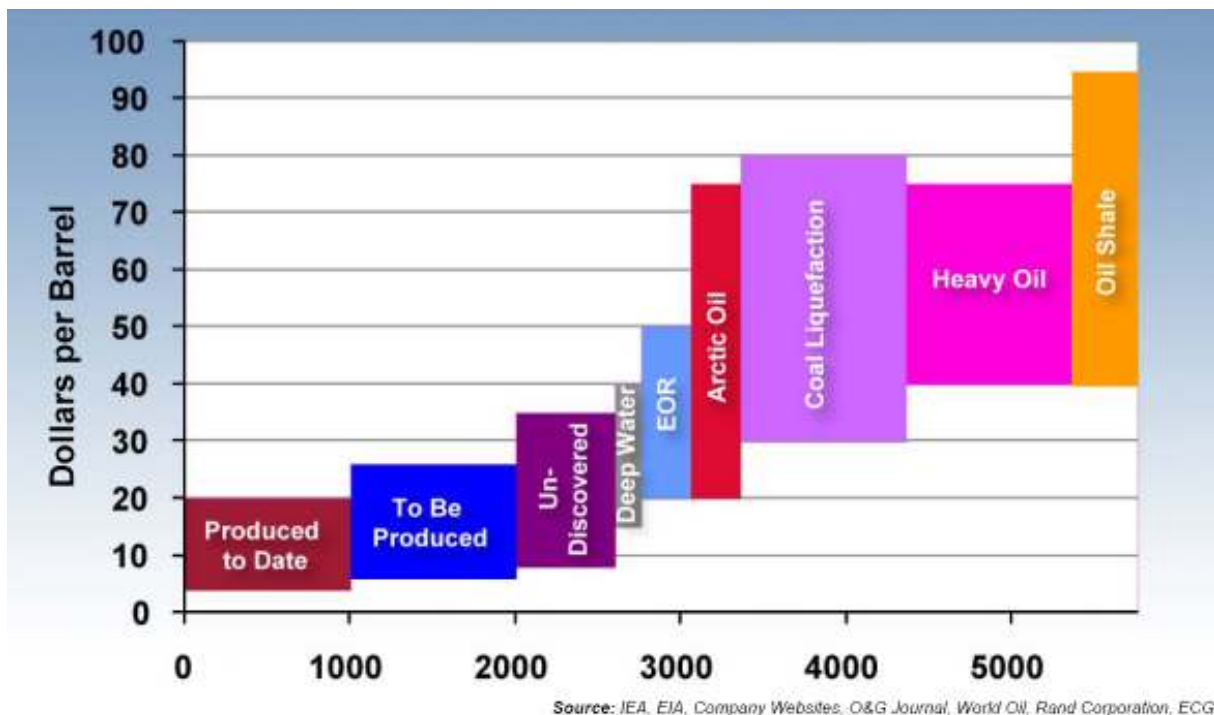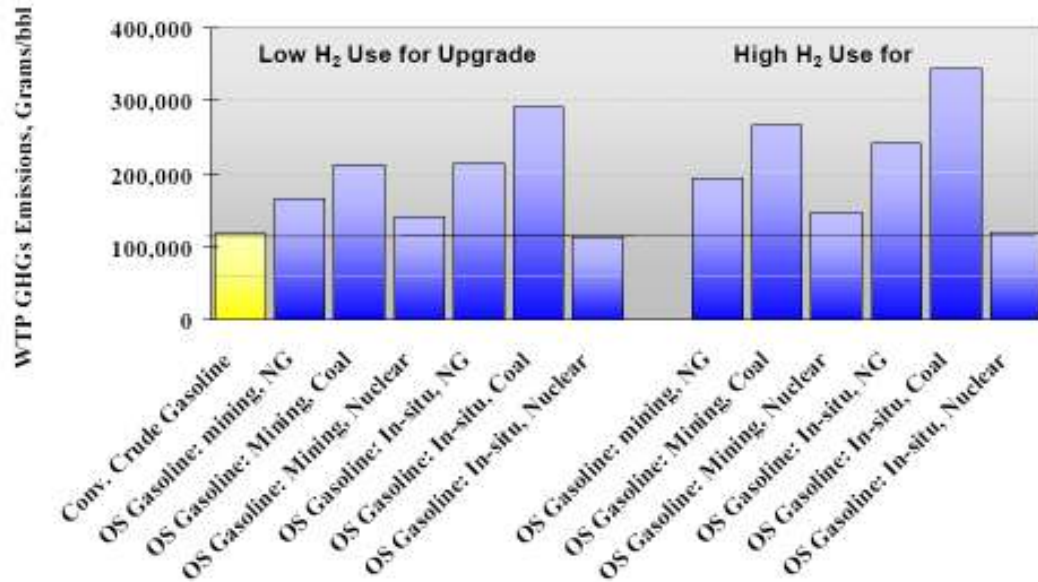Source: IEA, EIA, Company Websites, O&G Journal, World Oil, Rand Corporation, ECG

**Figure 11.2 GHG Emissions Associated With Gasoline Production From Oil Sands
Compared With Emissions from Conventional Crude Oil Gasoline Production**

Source: Michael Wang, "Overview of GREET Model Development at Argonne"
         March 18, 2008

The implications for GHG emissions are very significant at the margin. The choice of producing an additional gallon of fuel from tar sands versus ethanol clearly suggests that tar sands generate 150–300% more direct greenhouse gas emissions than ethanol. If the next incremental gallon of fuel is produced from one of these sources, the choice is clear and the comparison to conventional crude sources is irrelevant.

XII. CONCLUSIONS

Based on the hard scientific information available, quantifying the precise level of GHG emissions, especially indirect emissions, is a nebulous task at best. The EPA, as required by law, proposes to analyze GHG emissions associated with the production of biofuels including both direct emissions and indirect emissions associated with land-use change. A review of the scientific literature suggests that the direct GHG emissions associated with ethanol production are fairly well established for historical production techniques based on a particular set of production assumptions. Nevertheless, rapidly emerging technology that is substantially changing the productivity and co-products of the industry, as well as the power sources for the ethanol plants, will likely cause GHG emissions associated with biofuels to be overstated until the ethanol industry fully explores new as well as existing technologies. The EPA's choice of the FASOM model as an analysis tool for U.S. GHG emissions associated with agriculture is appealing because of the breakout of the key drivers of agriculture's GHG emissions, allowing the user to incorporate trends and new technologies that affect those parameters. Scenario analysis that incorporates new technologies and their resulting effects on GHG emissions will be especially important in correctly quantifying GHG emissions. Emerging technologies that reduce nitrogen fertilizer requirements by as much as 40–60%, increase drought tolerance, and combine existing genetics into "stacked" traits offer the promise of radically changing both the direct and indirect GHG emissions associated with agriculture.

A more troublesome problem is the quantification of GHG emissions associated with indirect land-use change. The EPA proposes to utilize the CARD-FAPRI models to analyze impacts of changes in biofuels policies on land-use in other countries and then convert the land-use change into GHG emissions. There are several difficulties with this approach. First and foremost, the GHG emissions associated with land conversion are not well understood and

are subject to considerable error, possibly in excess of 50%. Second, measurement of the types of land brought into production is imprecise at best. Satellite technology is promising, but clearly does not yet offer definitive identification of deforestation that is then converted to cropland. The data on deforestation reported by FAO also appear to be suspect given recent revisions as large as 30%.

Third, analysis by Searchinger et al. that utilizes the results of the CARD-FAPRI model is not consistent with the experience of 2007/08. Searchinger et al. conclude that additional U.S. biofuels production will result in more corn acreage to support biofuels, less soybean acreage, and a reduction in U.S. corn and soybean exports. Yet, the actual experience of 2007/08 suggests growing U.S. exports at the same time as record corn for ethanol use and soybean oil for biodiesel use. Clearly. this is only one year, but it is not clear that U.S. exports will fall dramatically (as suggested by the CARD-FAPRI analysis) as a result of the increase in U.S. biofuels use. What is also troublesome for econometric models is the recent level of world commodity prices. Econometric models of world agriculture were estimated over periods of much lower prices and may not provide as reliable estimates in the current situation, given that there were no historical observations as high as current commodity prices. If the CARD-FAPRI model is to be utilized for land-use change analysis, it should be available for public review like the GREET model along with historical performance estimates, so that the strengths and weaknesses of the model can be more precisely identified. Finally, there are several drivers of land-use change outside of biofuels. As incomes grow in developing countries, the populations seek to improve their diets. For many developing countries, this improvement leads to additional meat and vegetable oil consumption. Additional meat and vegetable oil consumption is the primary driver of demand for additional feed grain and oilseed production, accounting for over half of global demand growth.

The difficulty in measuring the indirect GHG emissions associated with land-use change, and particularly the susceptibility to error, suggests that further research is needed in this area. Analysis of the international effects of land-use change are particularly suspect given measurement problems, debate over GHG emission associated with different types of land-use change, competing drivers of land-use change, and correct measurements of crop area responsiveness in the current situation of high commodity prices. In a letter to the California Air Resources Board, Alex Farrell notes, "there is no well-accepted value for GHG emissions due to changes in land use because of increased biofuel production…These calculations are difficult and demand subjective judgments about methods and parameters…" The consensus of much of the scientific community regarding GHG emissions from indirect land-use change is that more research is needed to effectively identify these impacts. In this case, the policy appears to be ahead of the science in regulating what science cannot yet measure. If land-use change is to be considered, the most defensible estimates are to consider the direct impacts of land-use change in the United States, where measurement is more precise and the cause can be more precisely identified.

Critical to future analysis of any alternative fuels is that the analysis be done at the margin. The science is pretty clear with respect to the direct GHG gas emission associated with an additional gallon of petroleum from tar sands versus an additional gallon of ethanol. Utilizing crude oil as the standard against which to measure all alternative fuels is useful, but the critical analysis must be at the margin and depends on the alternative feedstock sources for that next gallon of fuel to be produced.

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