

# Biofuel Supply Chain Challenges and Analysis

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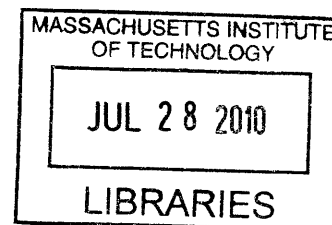
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# **Biofuel Supply Chain Challenges and Analysis**

by

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Submitted to the Engineering Systems Division  
on May 7, 2010 in Partial Fulfillment of the  
Requirements for the Degree of Master of Engineering in Logistics

## **Abstract**

Liquid fuels such as gasoline and diesel are traditionally derived from petroleum. Since petroleum has the potential to be exhausted, there is interest in large scale production of fuels from renewable sources. Currently, ethanol and biodiesel are liquid fuels that are mainly derived from field crops. This paper examines the supply chain challenges and issues that exist for bringing biofuel production up to scale. One major challenge that exists is how to transport the feedstock from a farm to a refinery in the most cost efficient manner. One way to improve transportation efficiency of feedstock is to increase the energy density of the feedstock. However, increasing the density of a feedstock comes with a cost. We use switchgrass as a case study and examine the tradeoff between higher transportation costs in transporting a less energy dense feedstock to processing a feedstock to increase its energy density. We show that creating ethanol from switchgrass in the United States is not competitive in price to gasoline without government subsidies, but as the supply chain matures, efficiencies gained will narrow the gap.

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# **1 Introduction**

During the past ten years, the United States has seen a great deal of growth in the liquid biofuel sector. A biofuel is a fuel that has been generated from a living or recently living organism. The biological matter is known as a “feedstock” before it is converted into a biofuel. The organic nature of the feedstock makes energy sources considered “renewable.” The two dominant liquid biofuels used in transportation are ethanol and biodiesel, and we will focus our discussion on these two products. First, we discuss the different types of feedstocks that can be used to produce these biofuels. Next, we discuss supply chain challenges for the biofuel industry. Last, we dig deep into the logistic issues involved in switchgrass to ethanol conversion starting at the farm and ending at the pump. Finally, a cost analysis of switchgrass is given for six combinations of harvesting, preprocessing, and production scale options. The methods discussed differ by the way the switchgrass has been processed to increase the energy density of the feedstock during transportation.

## **1.1 Ethanol Background**

Ethanol has been envisioned as a fuel for the automobile for over a hundred years. The first mass produced car, the Ford Model T, was designed to run on pure ethanol. In the time since, cars have strayed away from being able to run on pure ethanol. Ethanol is typically mixed with petroleum based gasoline. A typical car in the United States can run on a mixture called E10. This nomenclature means the fuel has 10% ethanol and 90% gasoline. The U.S. does have blends

which go up to E85, 85% ethanol and 15% gasoline. However, E85 blend requires a special engine to accept this fuel. These vehicles are called “flex fuel” vehicles.

Figure 1 below shows the ethanol production, consumption, and importing of ethanol in the U.S. As the figure shows, in 2001 there was about 1.8 billion gallons of ethanol consumed in the U.S. Contrast this with 9.2 billion gallons consumed in 2008, and in just seven years the ethanol consumption has grown by over 520% (USDOE, 2010a). As the market grew and continues to grow, the supply chain must grow alongside and adapt to gain efficiencies and economies of scale where appropriate.

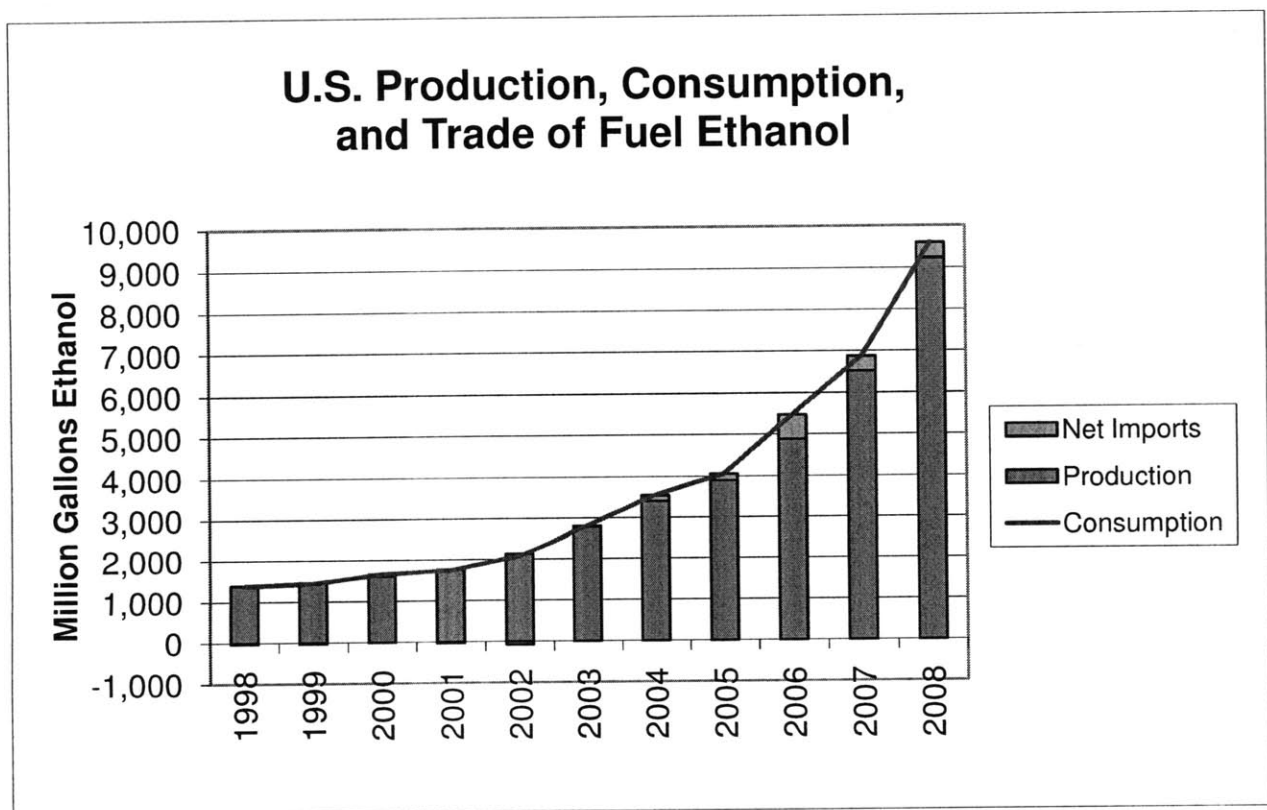


Figure 1. U.S. Consumption of Ethanol. (source: <http://www.afdc.energy.gov/afdc/data/fuels.html>)



## 1.2 Biodiesel Background

Biodiesel is another liquid biofuel that can be used to replace a traditional incumbent fuel. Biodiesel is similar to ethanol because it can also be blended with its fossil fuel counterpart, diesel. It also has the same naming mechanism. A mixture of 20 percent biodiesel, 80 percent diesel is called B20. B20 is commonly the highest blend which diesel engines will use without voiding the engine warranty. Pure biodiesel can only be run in special diesel engines without being blended.

Figure 2 below shows the production, exports, and consumption for biodiesel in the United States. The amount of biodiesel produced in the U.S. is roughly twenty times less than ethanol. However, biodiesel's growth on a percentage basis is dramatic. The amount of biodiesel consumed in 2008 was over thirty times more than the amount of biodiesel consumed in 2001. This rapid growth is expected to continue into the future as long as governmental mandates and subsidies for renewable fuels exist.

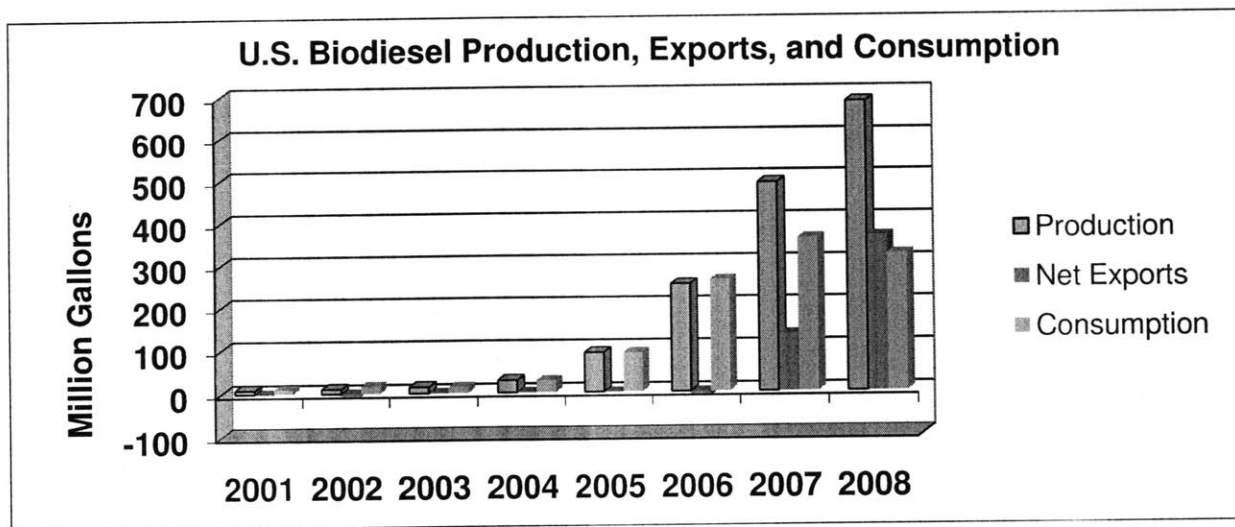


Figure 2. U.S. Biodiesel Production, Exports, and Consumption.  
([http://www.afdc.energy.gov/afdc/data/docs/biodiesel\\_production\\_consumption.xls](http://www.afdc.energy.gov/afdc/data/docs/biodiesel_production_consumption.xls))

## **2 Feedstock**

In this section, we examine multiple feedstocks used to create biofuel which show promise to be brought up to scale in the United States. Feedstocks will be examined for both ethanol and biodiesel, as feedstocks for each have different characteristics. At the end of the broad feedstock overview for ethanol, corn and switchgrass are examined in further detail. For ethanol, corn has been the dominant feedstock thus far, but switchgrass has shown promise since it can be grown with high yields in a variety of places. Next, after a brief overview of biodiesel feedstock, soybean and canola are discussed. Soybean has enjoyed a similar position in the biodiesel industry when compared to corn in the ethanol industry. It is the incumbent feedstock, but canola has shown promise with potential for high yields on a per acre basis.

### **2.1 Feedstock for Ethanol**

Ethanol is most commonly created through a process which first converts starches from biological matter to sugars. The sugars are then fermented to produce ethanol. In this section, we give multiple examples of ethanol feedstock followed by two feedstocks with potential to be brought up to scale: corn and switchgrass. In this section, yields will be given in terms of gallons of ethanol produced, and then a gasoline gallon equivalent number is provided as well since one gallon of ethanol is not energetically equivalent to a gallon of petroleum derived gasoline. Energy content of fuels is typically given based on British Thermal Units (BTU) and it takes roughly 1.5 gallons of ethanol to produce the same energy content as a single gallon of gasoline.

### **2.1.1 Virgin Feedstock**

A feedstock is considered virgin feedstock if it is created from a crop whose intended primary purpose is to be converted into a biofuel. Two types of virgin feedstock examined are grains and non-grains. An example of non-virgin feedstocks is recycled feedstock. Recycled feedstocks used to create ethanol are typically forest residue or organic material leftover from a crop harvested for food.

#### **2.1.1.1 Grains – Corn, Wheat, and Sorghum**

Corn, also known as maize, is the most widely grown food crop in the United States, and it is also the most commonly used feedstock in ethanol production in the United States, consisting more than 92% of feedstock used (USDOE, 2009b). In 2010, 13.1 billion bushels of corn are estimated to be produced domestically in the United States, and of this amount, 4.2 billion bushels of corn, or 38.4% of domestic production, are estimated to be used for ethanol production (Food and Agricultural Policy Research Institute [FAPRI], 2010). As recently as 2004 there was just over a billion bushels of corn being used to produce ethanol (FAPRI, 2010). The rapid growth of corn-based ethanol production may be linked the increased price of corn for food use since the amount of corn being used for ethanol is outpacing the increases in yields per acre and population growth.

Wheat is a grass cultivated worldwide, and originated from the Fertile Crescent region of the Western Asia. According to the Food and Agriculture Organization of the United Nations, wheat is the third most-produced cereal in the world (2010). The top world producer of wheat is China, which produced 109 million tonnes in 2007, followed by India with 75.8 million tonnes, and the

United States with 56 million tonnes (Food and Agricultural Organization of the United Nations [FAO], 2010). The traditional usage of wheat is in food and beverage production. However, ethanol production with wheat is maturing rapidly in the United Kingdom (Pagnamenta, 2009). It is seen as a promising biofuel feedstock for regions which are not optimal for growing corn. Two recently opened ethanol refineries in the UK are expected consume 2.3 million tonnes of wheat, and there is a possibility that ethanol production would make the United Kingdom a wheat importer for the first time in its history (Pagnamenta, 2009).

Sorghum is a tall annual plant (*Sorghum vulgare*) and belongs to the family Gramineae. This plant looks similar to corn and has similar usages. It is estimated that sorghum originated in Africa, and it historically has thrived in warm regions of Africa and Asia. Sorghum is known for its strong drought resistance and this is an attractive quality of the crop to potential importers, including the United States (“Sorghum”, 2008). Sorghum can be grown on marginal land and also has broad agro-ecological adaptation. Moreover, sorghum uses nutrients efficiently, and the growth cycle of sorghum is about four months, relatively short compared with other grains (Sweet Fuel Project, 2010). The production of sorghum can be highly mechanized, so it has low labor costs. These advantages make sorghum attractive as a future feedstock for ethanol. 383 million bushels of sorghum are expected to be produced in the United States in 2010 (FAPRI, 2010).

#### **2.1.1.2 Non-grains – Sugarcane, Sweet Potato, and Switchgrass**

Sugarcane is any of six to thirty-seven species (depending on taxonomic system) of tall perennial grasses of the genus *Saccharum*. Sugarcane is an Asian-native tropical grass and known to be first cultivated in India. Because of its large terminal panicle and noded stalk,

sugarcane appears to be similar to corn and sorghum (“Sugarcane”, 2008). Sugarcane offers a high energy balance and high greenhouse gas (GHG) reduction so is considered to be sustainable. Ethanol production from sugarcane has not been shown to have significant impact on food supply or prices in Brazil. They produced a third of the total world sugarcane production in 2007, by producing 550 million tonnes (metric tons) (FAO, 2010). This makes them the biggest producer of sugarcane in the world. Due to this large amount of sugarcane production, ethanol is widely used in cars in Brazil. In Florida, whose climate is similar to Brazil’s, one acre of sugarcane field yields roughly 405 gallons of ethanol (Rahmani & Hodges, 2006). This number is derived under the assumption that only sucrose, sugar, is used for the ethanol production. After Brazil, India is the 2nd largest worldwide producer of sugarcane with production of 355 million tonnes, and the United States is 9th worldwide in sugarcane production with 27.8 million tonnes (FAO, 2010).

Sweet potato (*Ipomoea batatas*) is an annual root plant and belongs to the family of Convolvulaceae. Its root is starchy and sweet so it is commonly used as food. Despite its name, the sweet potato is not closely related to the potato (*Solanum tuberosum*). Sweet potatoes are a member of the morning-glory family (Convolvulaceae), while potatoes belong to the Solanaceae family, along with tomatoes, red peppers, and eggplant (“Sweet Potato”, 2008). The sweet potato production in the United States in 2007 amounted to 1.8 million pounds (about 837,000 tonne) and is growing moderately (FAO, 2010). There has been an increasing amount of research dedicated to analyzing its viability as a future feedstock. Researchers from North Carolina State University reengineered the sweet potato and improved the starch content in it. Although it does not taste as good as normal sweet potato, this new sweet potato can produce twice the starch content of corn, which can be broken down into sugars for ethanol production (NCSU, 2007).

However, the high transplant cost of sweet potatoes still remains a challenge. Sweet potatoes are planted by manually transplanting them to the ground. Craig Yencho, an associate professor of Horticultural Science at N.C. State, is trying to find a way to plant sweet potatoes in the same way Irish potatoes are being planted, which is mechanically planting 'seed parts' to the ground. (NCSU, 2007) If they successfully achieve this goal, the planting cost would be reduced by half, and ethanol production with sweet potatoes can be much more cost effective and feasible when compared with ethanol production with corn (NCSU, 2007).

Switchgrass (*panicum virgatum*) is a perennial grass which originated from warm regions of North America, and is widely distributed in Mexico, the United States, and Southern Canada. Switchgrass has a deep and strong root system so it can be grown on marginal land, not suitable for the production of most crops such as corn. Therefore, the land used for the production of food crops does not need to be sacrificed to grow switchgrass. Switchgrass has been conventionally used as ground cover to conserve soil and prevent erosion, and is suitable to grow on land used for foraging and grazing (Rinehard, 2006). In addition, switchgrass can also be used as a feedstock for biofuels such as ethanol, and it can be genetically altered to produce biodegradable plastics as a byproduct. The use of switchgrass for the production of biodegradable plastic was investigated starting in 2008 by Metabolix, a company based in Cambridge, Massachusetts. According to its website, [www.metabolix.com](http://www.metabolix.com), the Metabolix research team has developed a way to produce polyhydroxyalkanoates (PHAs, a biodegradable polyester) from switchgrass, adding to the value of the crop.

### 2.1.2 Residues

Residues from crop processing, logging and forest operations can be used for ethanol production. Theoretically, all materials that can be broken down to sugar have potential as feedstock for ethanol. According to the researchers from Michigan State University, 130 billion gallon of ethanol can be produced annually from crop residues and wasted crops. Total dry wasted crops in the world could be converted to 13 billion gallon of ethanol, and other lignocellulosic biomass, such as corn stover, sugarcane bagasse, and wood residues, could be converted to 117 billion gallon of ethanol annually (Kim & Dale, 2004). However, there should be careful assessment on the use of crop residue for ethanol production. A researcher from Kansas State University argues that removal of crop residues from agricultural cropland would directly influence the quality of cropland and require the change of field management practices (Blanco-Canqui, 2010). In addition, the logistics of the crop residues is not cost-efficient, since the energy density of the residues is so low. At the same time, the production of ethanol from this residue is more costly than production from crops.

### 2.1.3 Corn



Figure 3. Corn. (source: <http://en.wikipedia.org/wiki/File:Koeh-283.jpg>)

This section goes into greater detail about the current corn consumption in the United States. Corn is primarily grown in the upper Midwest, but it is not limited to this area. It grows here because the soil allows high yields and there are established croplands. We examine sample yields for corn in different parts of the U.S and explain two different ways to convert corn into ethanol. These processes, known as wet milling or dry milling, are discussed at the end of this section.

#### 2.1.3.1 Current Ethanol Production From Corn

In the United States, corn historically has been predominantly grown for feed, sweeteners, cereals, or sold as an export. In recent years its use as the primary feedstock for ethanol has shown exponential growth. As shown below in Figure 4, the amount of corn being used for ethanol started to grow greatly starting around 2001. According to the Biomass Energy Data



Book, 706 million bushels of corn were being used for conversion to ethanol in 2001 (Wright, Boundy, Badger, Perlack, & Davis, 2009). When compared to 2008's 3,600 million bushels of corn harvested for ethanol production, this shows over 500% growth in that short period of time (USDOE, 2009c). This equates to 30% of all domestic corn consumption in 2008, rising to an expected 38.4% in 2010 (FAPRI, 2010). It has remained the dominant feedstock for ethanol. In 2006, over 92% of ethanol production was derived from corn, roughly 4,500 million gallons (USDOE, 2009c).

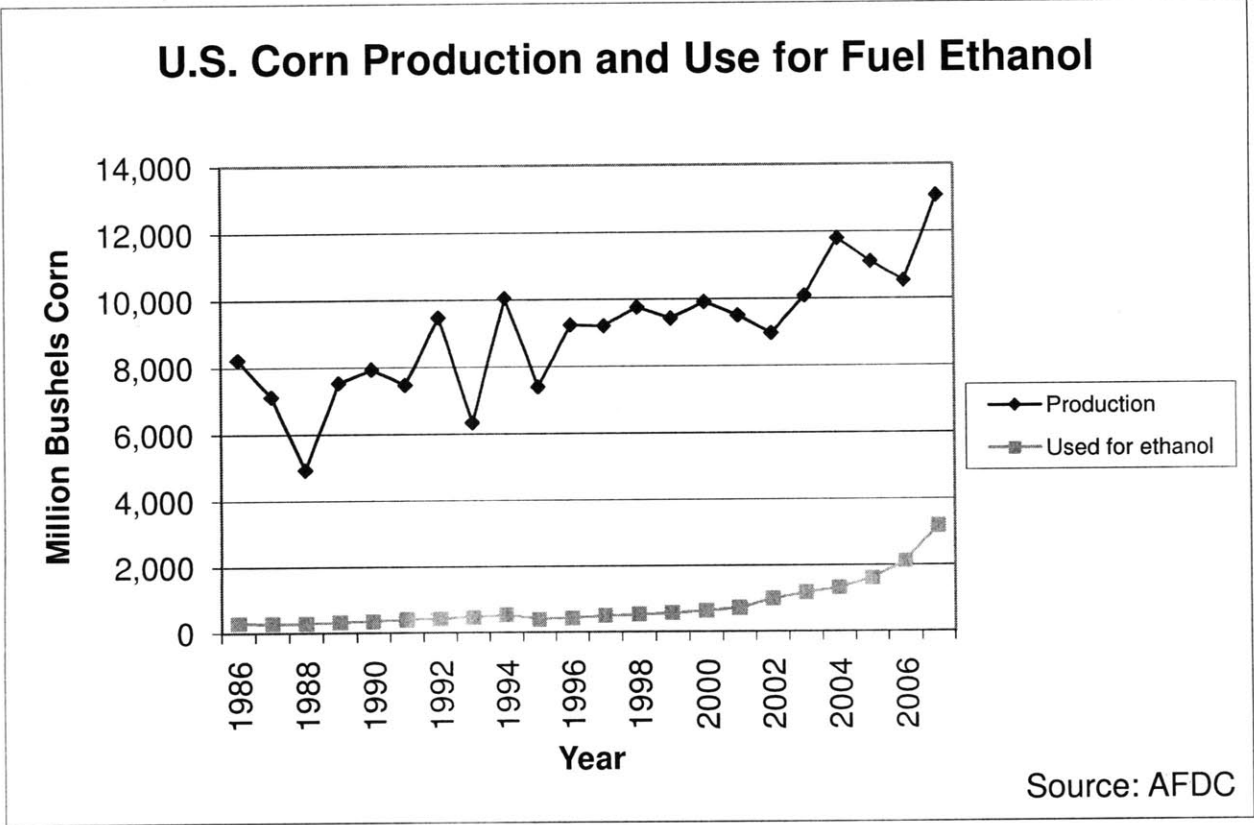


Figure 4. U.S. Corn Production and Use for Fuel Ethanol. (Source: USDA National Agricultural Statistics Service and Economic Research Service)

### 2.1.3.2 Location of Crop and Yield

As Figure 5 below shows, corn is primarily grown in the upper Midwest in a region known as the “corn belt.” States with high amounts of corn farming are: Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, Nebraska, Ohio, South Dakota, and Wisconsin. Illinois and Iowa are the two largest corn-producing States in the United States, producing just under 30% of the national corn crop (USDA, 2008b).

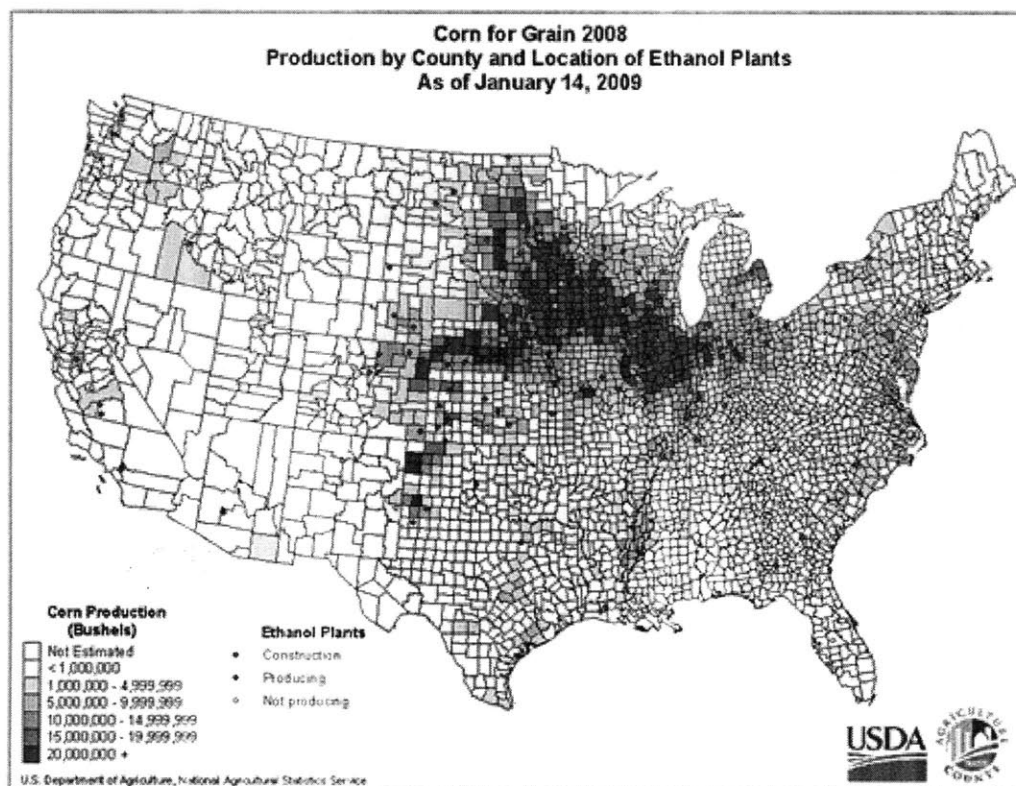


Figure 5. Corn for All Purposes 2008 Planted Acres by County. (source: [http://www.nass.usda.gov/Charts\\_and\\_Maps/Ethanol\\_Plants/U.\\_S.\\_Ethanol\\_Plants/index.asp](http://www.nass.usda.gov/Charts_and_Maps/Ethanol_Plants/U._S._Ethanol_Plants/index.asp))

Figure 5 also shows the location of ethanol plants, where corn is the primary feedstock used to produce ethanol. As one would expect, the ethanol plants are commonly located closely

to the fields where corn is grown. This is because corn has less energy density than ethanol. It is more cost efficient to transport ethanol fuel longer distances rather than the feedstock because of this energy density difference. Hence, the fuel is produced in the upper Midwest and shipped in its most energy dense stage, as a liquid fuel, to where the demand exists.

It is estimated that in 2010, farmers in the United States will have a yield of 165.2 bushels per acre, leading to 444.4 gallons of ethanol of yield per acre for wet milled corn or 452.6 gallons if it is dry milled (FAPRI, 2010). This equates to a gasoline gallon energy equivalent of 296.3 gallons of gasoline for wet milled corn and 301.7 gallons of gasoline equivalent for dry milled corn. Traditionally the amount of crop grown per acre and efficiency of the process to convert corn into ethanol will both increase from one year to the next. These trends both lead to an increase of ethanol produced per acre of corn planted from one year to the next. However, one must keep in mind that yields do vary from region to region. In 2008, the USDA published *Agricultural Statistics* which 2007's contained corn yields per state. The State yielding the lowest bushels per acre of corn planted was Alabama with 79 bushels per acre; this is in contrast to Washington which yielded 210 bushels per acre. The two States which produce the most corn, Iowa and Illinois had statewide yields of 171 and 175 bushels per acre respectively (USDA, 2008b).

### **2.1.3.3 Wet Milling and Dry Milling**

To be converted into ethanol, corn must undergo a fermentation process. A different process, cellulosic conversion, is discussed for switchgrass being used as a feedstock. There are two different processes for creating ethanol from corn: dry mill or wet mill processing. Originally wet milling was the primary source of ethanol capacity, but now dry-milling is

dominant. Dry milling plants are much smaller than wet-milling plants and require much less energy to operate (USDOE, 2009d).

The U.S. Department of Energy describes both the wet milling and dry milling process on its webpage titled “Starch- and Sugar- Based Ethanol Production” (2009d). A high level overview for both milling processes follows which was summarized largely from this webpage.

In dry milling, the corn is ground to a pulp the consistency of flour. Next, water and enzymes are mixed with the corn, with an increased temperature to change the starches to glucose. Now the mixture is cooled and yeast is added which ferments the mash producing ethanol. Figure 6 below shows the dry milling process from feedstock to end product. Note there are multiple byproducts of the process which all contribute to the profitability of the crop. For one there is the ethanol to be used as a fuel. Other outputs are dried distillers grains with soluble (DDGS) used in livestock feed due to its high protein content and also carbon dioxide released during fermentation can be sold to the soft drink industry (Renewable Fuels Association [RFA], n.d.).

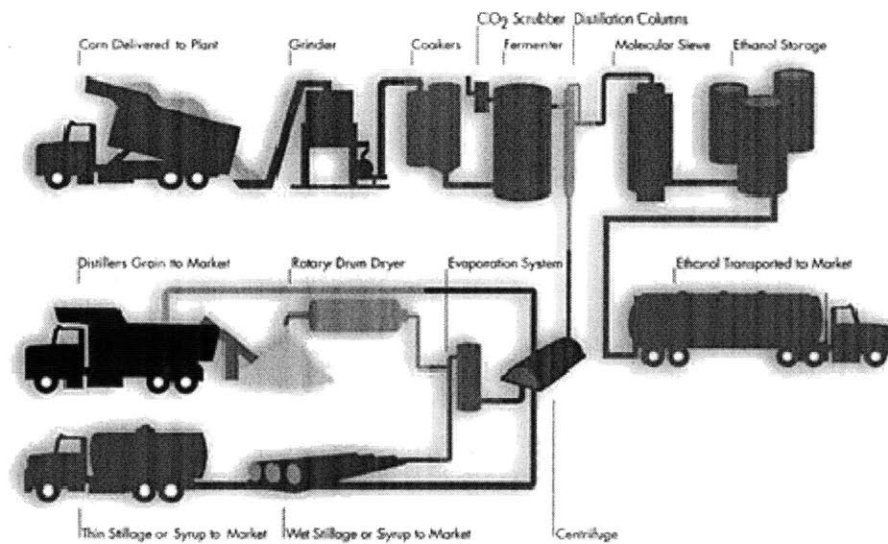


Figure 6. Dry Milling Process. (source: <http://www.ethanolrfa.org/resource/made/>)

For the wet-milling process, the main outputs of the process are ethanol and corn sweeteners. First, the starch and protein in the corn grain are separated by placing the grain in hot water. The solution is then ground and processed, extracting byproducts via a set of steps which ends with the starch being dried to produce sweeteners and the sugars fermented into ethanol (USDOE, 2009d). Figure 7 shows the wet milling process for corn. Similar to dry milling, there are also other outputs to the wet milling process than only ethanol. The Renewable Fuels Association lists multiple byproducts which add to the processes' profitability. (n.d.) Corn oil is one byproduct extracted from the corn. Additionally, a corn gluten meal product of the wet milling process is sold to the livestock industry. Completely unrelated to the food industry, the residual water leftover from the process can be used as an alternative to salt to melt ice from roads. Lastly, any starch leftover can be fermented into ethanol similar to the dry mill process, sold as corn starch, or processed into corn syrup (RFA, n.d.).

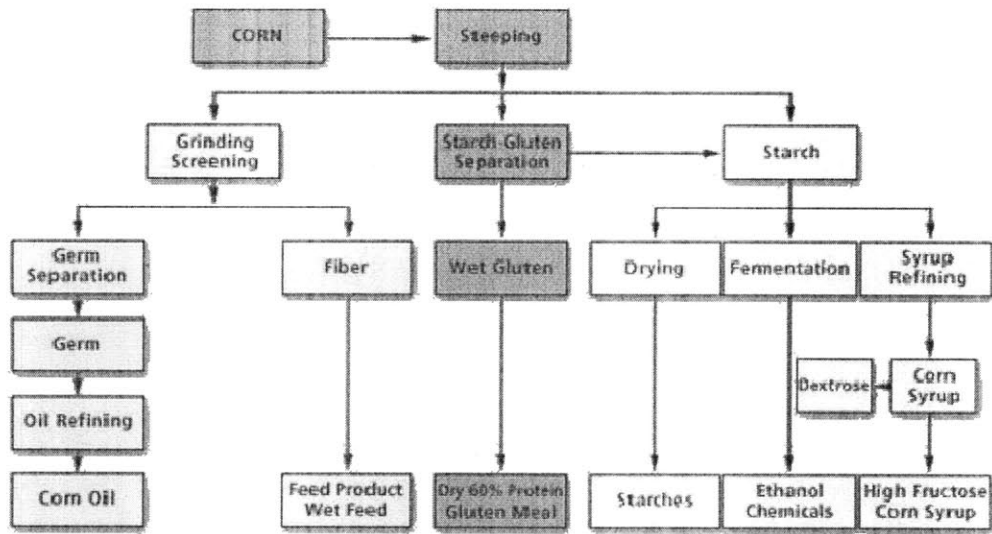


Figure 7. Wet Milling Process. (source: <http://www.ethanolrfa.org/resource/made/>)

Dry milling and wet milling are different processes and consequentially both have different yields of ethanol per bushel of corn. Dry milling currently produces 2.74 gallons of ethanol per bushel of corn and wet milling produces 2.69 gallons of ethanol per bushel of corn (FAPRI, 2010). Thus, dry milling is slightly less than 2% more efficient for ethanol conversion than wet milling. Dry milling is more common than wet milling because it uses less energy per gallon of ethanol produced, and is typically optimized for ethanol production. (USDOE, 2009d).

## 2.1.4 Switchgrass



Figure 8. Figure of Switchgrass. (source: <http://en.wikipedia.org/wiki/File:PanicumVirgatum.jpg>)

This section goes into greater detail about the current state of switchgrass farming in the United States. Switchgrass is a native crop to the U.S. and can be grown in most areas across the country, but States such as North Dakota have a great deal of land available which could support switchgrass farming. We identify two different ways to convert switchgrass into ethanol, through biochemical or thermochemical conversion, and they are discussed at the end of this section.

### 2.1.4.1 Current Production

Switchgrass currently is not a major crop grown for biofuel, but it shows great promise. First, it is a native crop to North America, so it will naturally resistant to pests, diseases, and requires little fertilizer to achieve high yields (Bransby, n.d.). There are two main types of switchgrass, upland and lowland. Lowland switchgrass tends to be taller than upland

switchgrass, with lowland switchgrass reaching heights of 12 feet compared to upland's height of five to six feet (Bransby, n.d.).

Because switchgrass is a perennial grass, it is important to maintain switchgrass over the year to guarantee stable supply. It may take three or more years for switchgrass stands to firmly take place on the ground. Once settled, switchgrass stands would stay productive for 10 or more years (Oak Ridge National Laboratory [ORNL], 2008). To ensure the productivity, ample nitrogen and water should be supplied to the soil. Phosphate and potassium are also recommended to maintain nutrient-balanced soil (Samson, 2007).

Currently the market for switchgrass as an energy crop is extremely small. In fact, the United States Department of Agriculture's National Agriculture Statistics Service does not have data on the crop since its current market is so small.

#### **2.1.4.2 Location of Crop and Yield**

Switchgrass is an attractive feedstock because it can be grown in a great variety of soil and climate conditions. Yields in the Southeast of the United States appear to be the highest domestically, followed by the "Corn Belt" region, and the lowest yield is in the Northern Plains (Rinehart, 2006). Rinehart also mentions that switchgrass depletes the ground of a large amount of nitrogen so the farmer must take active measures to put additional nitrogen into the agroecosystem to maintain productivity. Figure 9 shows where sites for switchgrass farms are feasible (De La Torre Ugarte, Walsh, Shapouri, & Slinsky, 2003). There is little land available on the Pacific Coast or in the Rocky Mountains. However, the North Central region appears to have land which may be available if switchgrass production is scaled up.



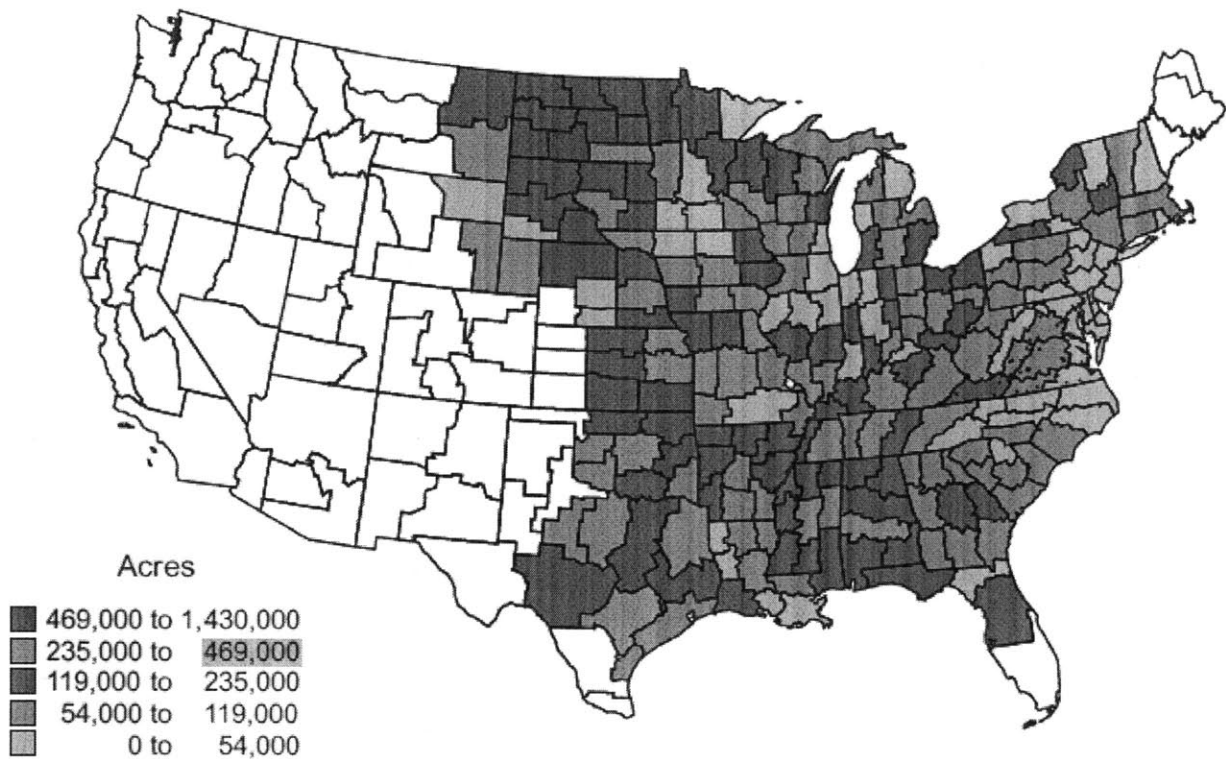


Figure 9. Land Available for Switchgrass. (source: <http://www.usda.gov/oce/reports/energy/AER816Bi.pdf>)

As stated above, the yield of the crop varies by location. For example, the Southeast can have a yield between 7-16 tons of crop per acre, and the “Corn Belt” can produce 5-6 tons per acre, and lastly, 1-4 tons per acre in North Dakota (Comis, 2006). The Oak Ridge National Laboratory estimates that one ton of switchgrass feedstock may be converted to 100 gallons of ethanol (Oak Ridge National Laboratory, n.d.). This would lead to a range of 100 gallons per acre at a low producing farm in North Dakota to a high end of 1,600 gallons of ethanol per acre at a high producing farm in the Southeast. This high end equates to a gasoline gallon energy equivalent of 1,066.7 gallons of gasoline per acre. Tradeoffs exist since high yield cropland is typically more expensive to purchase. The reverse can also be true as well: land which is cheap to purchase may not have high enough yields to be competitive and sustain economically viable switchgrass production.

### **2.1.4.3 Cellulosic Ethanol Production**

Currently there are few cellulosic ethanol manufacturers. However, since the technology shows great promise, there is a great deal of research rapidly advancing the state of the art. Two conversion processes are being considered for cellulosic ethanol conversion, biochemical conversion and thermochemical conversion.

The U.S. Department of Energy's Alternative Fuels and Advanced Vehicles Data notes there are two key steps for biochemical conversion: biomass pretreatment and cellulose hydrolysis (2009b). During pretreatment, the hellicellulose component of the biomass is broken down into simple sugars and these are then removed to be fermented. Then in cellulose hydrolysis, the remaining cellulose component of the biomass is reduced to the simple sugar glucose (USDOE, 2009b). Finally, the sugar is fermented to create ethanol. Figure 10 below gives a graphical description of the biochemical conversion process. The cost of the cellulosic ethanol process is estimated at \$2.20 per gallon with the enzymes costing \$0.30-0.50 per gallon, compared with \$0.03 per gallon for corn (Weeks, 2008). The cost of enzymes must come down significantly in order for cellulosic ethanol to be competitive. There are currently no large cellulosic ethanol producing refineries.

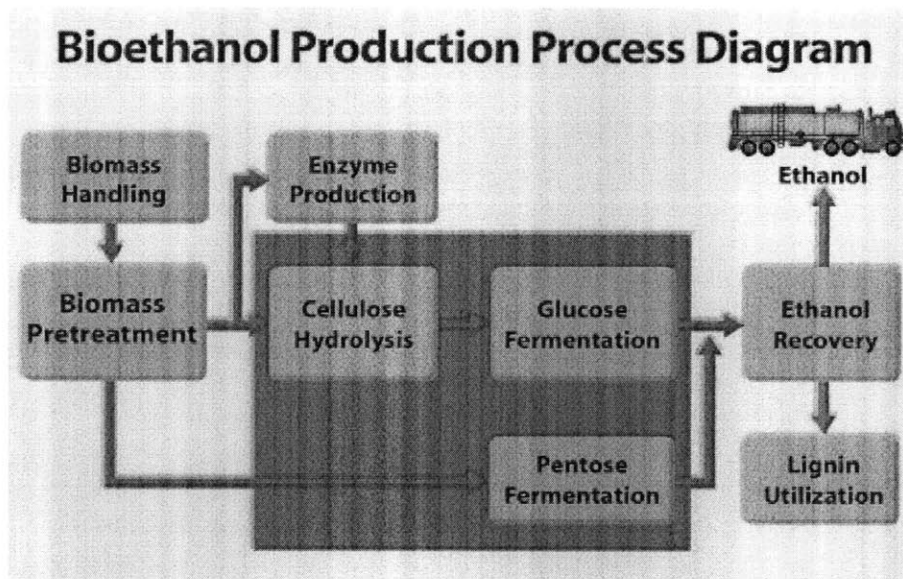


Figure 10. Bioethanol Production Process. ([http://www1.eere.energy.gov/biomass/abcs\\_biofuels.html#prod](http://www1.eere.energy.gov/biomass/abcs_biofuels.html#prod))

The Alternative Fuels and Advanced Vehicles Data Center also gives a description for a thermochemical conversion, which is different than the biochemical conversion (USDOE, 2009b). For a thermochemical conversion from switchgrass to ethanol, first chemicals are added to the biomass and then heat is applied to create syngas (carbon monoxide and hydrogen) which then is reassembled into ethanol (USDOE 2009b). Figure 11 shows the thermochemical process for changing a biomass such as switchgrass into ethanol.

## Schematic of a Thermochemical Cellulosic Ethanol Production Process

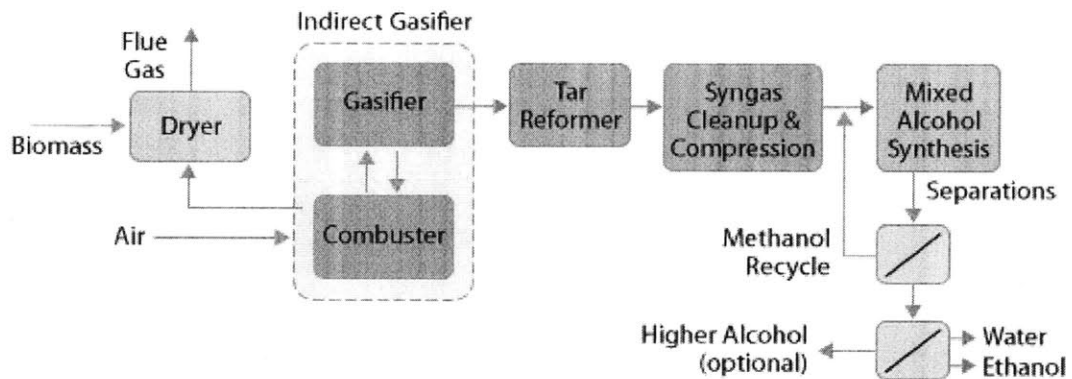


Figure 11. Thermochemical Cellulosic Ethanol Production Process. (source: [http://www.afdc.energy.gov/afdc/ethanol/production\\_cellulosic.html](http://www.afdc.energy.gov/afdc/ethanol/production_cellulosic.html))

### 2.1.5 Ethanol Conclusions

As has been shown, there are different facilities and methods required for producing ethanol depending on which feedstock is used. There are tradeoffs involved with using corn or switchgrass as the dominant feedstock. Currently corn being used as a feedstock is the most economical and prevalent, but it displaces land that would otherwise be used to produce food. Switchgrass is more expensive to refine, but it can be grown on marginal lands that likely would not be farmed. This translates into cheaper land investment for a dedicated switchgrass farm.

Below yields for different feedstocks are given in Figure 12. Data for Figure 12 is extracted from the book *Plan B 2.0: Rescuing a Planet Under Stress and a Civilization in Trouble* by Lester Brown in 2006 except the yield for switchgrass. The yield for switchgrass is calculated based on data in the research of Sokhansanj et al. in 2009 by using conversion rate of 0.38 liter  $\text{kg}^{-1}$ , which found in Schmer et al. (2007). As shown in the Figure 12, the yield of ethanol from switchgrass is higher than that from corn on a per acre basis, because switchgrass grows quite

tall and dense in a field. Switchgrass has number of other benefits. First of all, because of its perennality, switchgrass requires less tillage, there is also less soil erosion, and it needs less fertilizer than most field crops (Bransby, n.d.). Second, switchgrass grows well at almost any soil type in the United States. When Dave Bransby, a forage scientist at Auburn University, planted switchgrass on land which was futile after cultivation of king cotton for two centuries, switchgrass prospered (Oak Ridge National Laboratory, n.d.). Third, we can add value to the crop which does not relate to ethanol conversion. As mentioned above, one such example is Metabolix Inc. who look to improve the profitability of ethanol extraction from switchgrass by collecting bio-degradable plastic out of switchgrass as a byproduct.

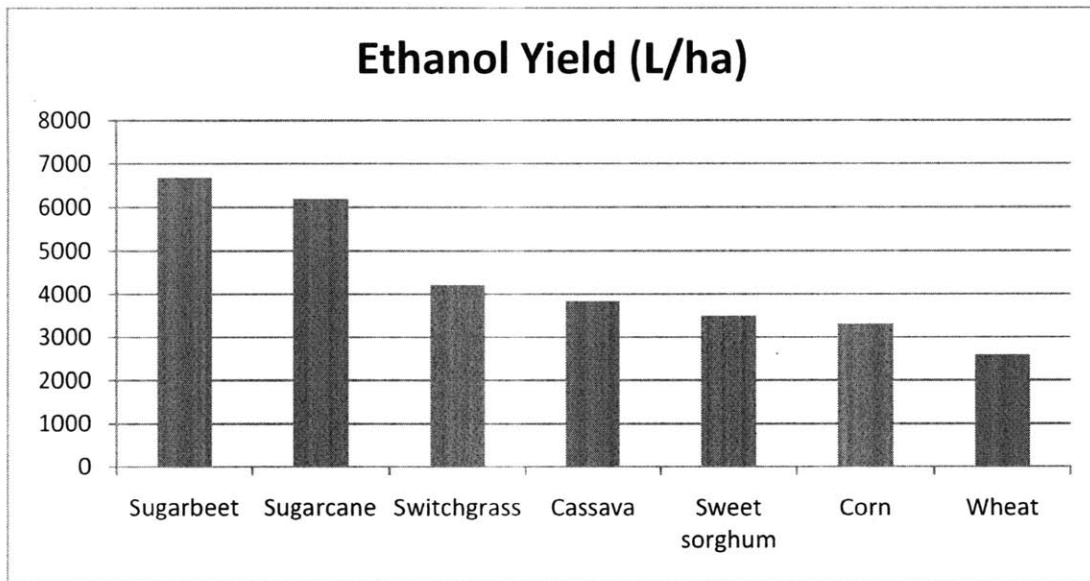


Figure 12. Yield of ethanol from each feedstock.

As the figure shows, there are feedstocks that produce higher yields than switchgrass and corn, but they are not economically viable due to the limited locations they can be grown.

## **2.2 Feedstock for Biodiesel**

There are several different types of organic material that can be used to produce biodiesel. Biodiesel is produced through a process which combines oils with an alcohol and a catalyst to form ethyl or methyl ester (Wright, Boundy, Bader, Perlack, & Davis, 2009). This section gives background information about potential feedstock which can be turned into biodiesel, and it ends with two oilseed crops with great potential to be brought up to scale for the production of biodiesel: soybean and canola. In this section, yields will be given in terms of gallons of biodiesel produced, and then a gasoline gallon equivalent number is given as well since one gallon of biodiesel is not energetically equivalent to a gallon of petroleum derived gasoline. Energy content of fuels is typically given based on British Thermal Units (BTU) and it takes roughly .88 gallons of biodiesel to produce the same energy content as a single gallon of gasoline.

### **2.2.1 Virgin Feedstock**

As noted in the feedstock for ethanol section above, there are two types of feedstock: virgin and recycled. Three types of virgin feedstock are examined for biodiesel: vegetable oils, animal fats, and algae.

#### **2.2.1.1 Vegetable oils – Soybean, Canola, and Sunflower**

A soybean is an oilseed that can be crushed to produce an oil which also can be a feedstock for biodiesel. There are two major products that come out of the bean crushing process, meal and oil. First, the oil is extracted from the soybean. According to the United States Department of Agriculture, eighteen to nineteen percent of a soybean's weight is oil, and this is extracted by a process known as "crushing" (USDA, 2008a). Soybean meal is what is left after

the bean has been crushed. The oil can be used as cooking oil, in food products, or as a feedstock for biodiesel. The meal is typically used as livestock feed since it has an extremely high amount of protein in it. Ninety-eight percent of the soybean meal produced domestically is used as feed for livestock. Also, soybean consists of 90% of the total U.S. oilseed crop (USDA, 2008a).

A feedstock that has been used as a dominant feedstock for biodiesel outside the US, particularly in Europe, is the oil extracted from canola. Canola is a variety of the crop known as rapeseed. Rapeseed oil is not fit for human consumption, so breeders created canola, which was able to be consumed without side effects. While the current canola footprint in the U.S. is small, it has been growing in the Northern Plains of the US. In the US, it grows in regions with a short, dry season where soybean or corn is not an attractive crop. Canada is a source of over half the world's canola/rapeseed oil export (Casséus, 2009) Canola is an oil seed, similar to soybean, where the seed is crushed and oil is extracted to leave meal. Canola meal is second to soybean meal as the largest protein meal in the world (USDA, 2010a). There is a price premium for canola oil over soybean oil due to increasing demand for canola for food use. The lower cost of soybean oil causes it to be a more attractive feedstock for biodiesel.

Similar to the other oilseeds, sunflower oil is also a potential feedstock for biodiesel. In the U.S., almost half of the sunflower seed produced is used for birdseed, snacks, and baking. The rest is crushed into oil and meal. The primary growing region for the sunflower crop in the U.S. is the upper Midwest. Sunflower oil has the same problem as canola. Its oil is in high demand for edible uses, and this causes the price to increase and make it more difficult to be a viable feedstock for biodiesel unless diesel prices are extremely high (USDA, 2009d).

### **2.2.1.2 Animal fats**

Animal fats have similar fatty acids as vegetable oils, so they are also a candidate feedstock to produce biodiesel. Large poultry, pork, and beef providers have started to use animal fat waste to produce biodiesel. In 2007, Tyson Foods partnered with large oil company ConocoPhillips and synthetic fuel producer, Syntroleum, to produce biodiesel. One third of all the animal fat in the U.S. is produced by Tyson Foods, so the company has access to a large amount of raw material (Anderson, 2007). Relationships like these are highly reliant on high fuel prices and government subsidies. This program was cancelled when the government subsidy was altered, making the program less profitable for Tyson Foods.

### **2.2.1.3 Algae oils**

Alga is a photosynthetic organism that lives primarily in water. Oils from algae are another potential feedstock for biodiesel. Two types of algae that can be used to produce the requisite oils are macroalgae and microalgae. Macroalgae can be seen with the naked eye. Conversely, microalgae cannot be seen without the help of a microscope. Microalgae have the potential to produce 250 times the amount of oil as soybeans per acre (Hossain, Salleh, Boyce, Chowdhury, & Naquiddin, 2008). The high yield potential of microalgae makes it an attractive feedstock when being brought up to scale. Currently, alga has not been brought to scale because of the high cost of capital to produce reactors at such a large scale. Also, research on how to produce high yields at a large scale is not in a mature stage making large scale production competitive.



### 2.2.2 Recycled waste vegetable oils

Waste products from other processes which leave oil as twaste provide the opportunity to recycle the oils into biodiesel. Restaurants are the logical source of waste vegetable oils. The amount of waste vegetable oil produced in the U.S. was estimated at 2.9 billion gallons (Environmental Protection Agency [EPA], 2009). This would be capable of offsetting almost 1% of the U.S. oil consumption. A major advantage of recycling vegetable oils is the price. Often times, waste oil can be procured very cheaply or even free from restaurants. However, collection of waste oils is labor intensive and requires a great deal of coordination with restaurants to pick up the waste oil. So while the feedstock may be cheap, costs add up in transporting the feedstock to a refinery. If there were trucks making runs to each restaurant for another purpose, there may be the opportunity to pick up waste vegetable oils and fill space that otherwise would be empty on a truck.

### 2.2.3 Soybean

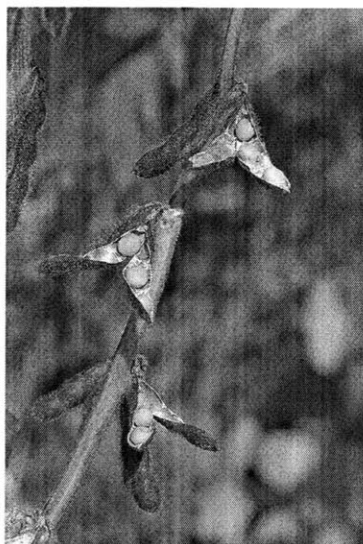


Figure 13. Soybean. (source: <http://en.wikipedia.org/wiki/File:Soybean.USDA.jpg>)

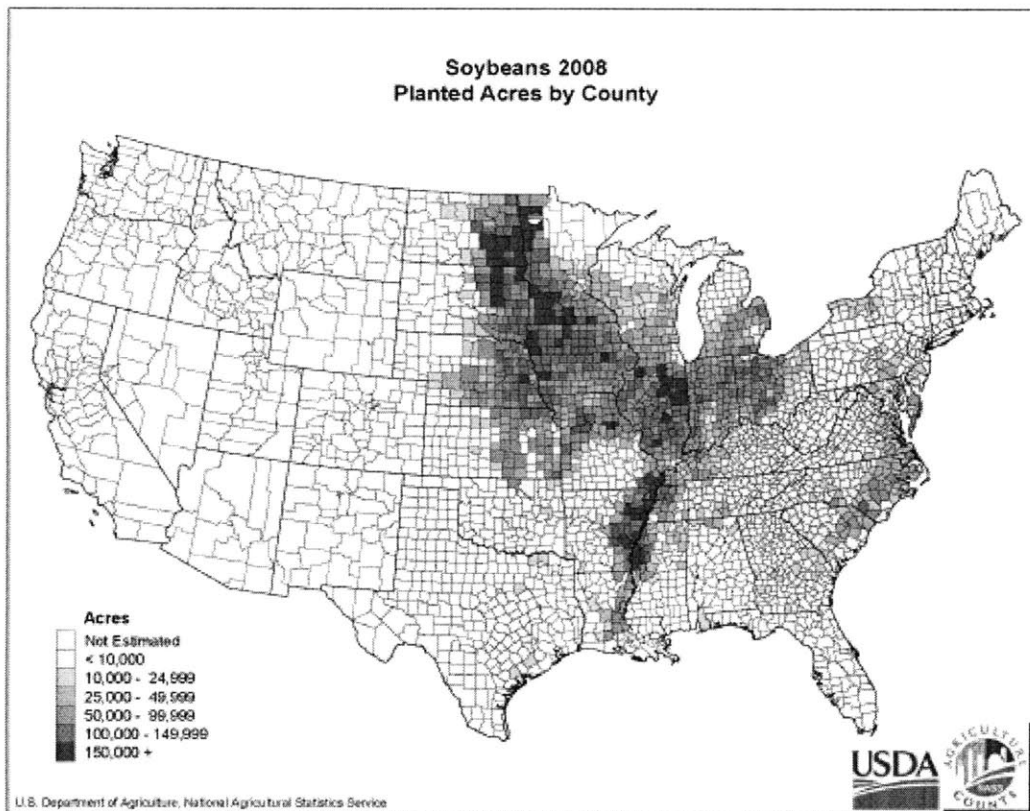
This section goes into greater detail about the current state of soybean farming in the United States. We discuss how soybeans are typically grown in the same areas corn is around the Midwest, and we give an average yield in terms of gallons of biodiesel produced per acre of harvested soybeans. Lastly, we discuss how the oil is extracted from soybeans and then refined into biodiesel for use as a liquid fuel.

### **2.2.3.1 Current Production**

Soybean is a crop which is increasingly in demand both domestically in the U.S. and abroad since it can be used as both food and a feedstock for biodiesel. In 2009, it is estimated that 1,904 million pounds of soybeans out of 18,753 million pounds of newly grown soybeans will be used for biodiesel production (USDA, 2010b). This equates to around 10% of the total soybean grown in the U.S. being used as a feedstock for biodiesel or 300 million bushels. This number is set to grow to 2,600 million pounds by 2013 (USDA, 2010b).

### **2.2.3.2 Location of Crop and Yield**

Similar to corn, soybeans are primarily planted in the Midwest in the “corn belt.” The major soybean producing states are Illinois, Indiana, Iowa, Minnesota, Missouri, Nebraska, and Ohio. Also, there are some counties in southeastern North Dakota with very high plantings. Figure 14 below shows the planted acreage by county.



**Figure 14. Soybeans 2008 Planted Acres by County.**  
(source: [http://www.nass.usda.gov/Charts\\_and\\_Maps/Crops\\_County/sb-pl.asp](http://www.nass.usda.gov/Charts_and_Maps/Crops_County/sb-pl.asp))

The Food and Agricultural Policy Research Institute (FAPRI) at the University of Missouri has put forth various yield predictions for the soybean crops in future years. In 2010, estimates show a yield of 44.0 bushels per acre of Soybeans. (FAPRI, 2010) After being crushed, 11.4 pounds of soybean oil will be extracted per bushel of soybeans, from which it takes 7.7 pounds of crude soybean oil to be turned into a gallon of biodiesel (FAPRI, 2007). Using these numbers as the basis for calculations, on average an acre of soybeans will yield 501.6 pounds of crude soybean oil, which can be used to create 65.1 gallons of biodiesel. This equates to a gasoline gallon energy equivalent of 66.4 gallons of gasoline.

### 2.2.3.3 Biodiesel Production from Soybean Oil

The first step once the soybean crop has been harvested is to extract the oil from the soybean. This is done through a process known as crushing. The soybeans are processed in a way that extracts the soybean oil and leaves a high protein meal which is then typically used as a high protein additive to animal feeds.

Biodiesel is created from the soybean oil that was extracted. Biodiesel is made up of chemical compounds called fatty acid methyl esters. The United States Department of Energy's Alternative Fuels and Advanced Vehicles Data Center explains the production of these esters (2010b). First the oils and fats go through a preprocessing step which removes water and contaminants. After pretreatment, the fats and oils are mixed with an alcohol, typically methanol, and a catalyst, typically sodium hydroxide. This process creates the chemical compounds methyl ester and glycerin of which the esters are used as biodiesel (USDOE, 2009a). Below in Figure 15, the process is further broken down in greater detail.

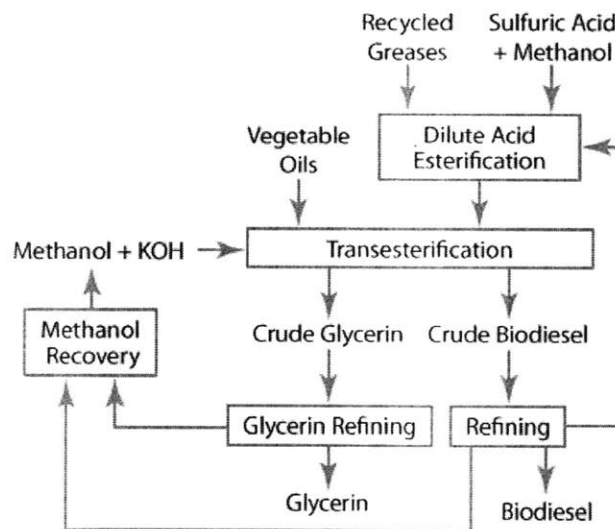


Figure 15. Schematic of Biodiesel Production Path.  
(source: [http://www.afdc.energy.gov/afdc/fuels/biodiesel\\_production.html](http://www.afdc.energy.gov/afdc/fuels/biodiesel_production.html))

## 2.2.4 Canola

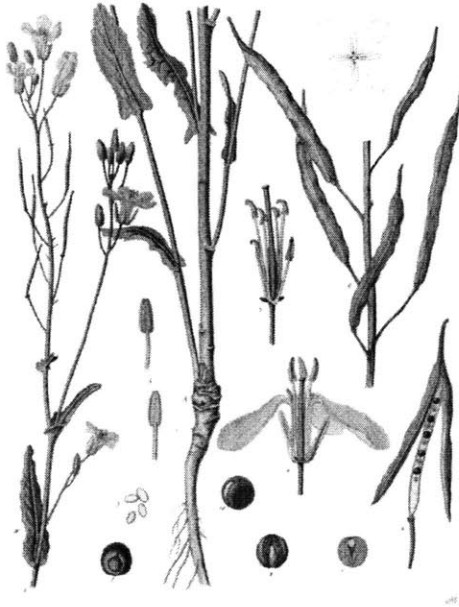


Figure 16. Canola. (source: <http://en.wikipedia.org/wiki/File:KoeH-169.jpg>)

In this section we go into greater detail about the current state of canola farming in the United States. We discuss how there is currently a shortage of domestic canola and the U.S. is reliant on importing canola oil. In the U.S., North Dakota supplies most of the domestic canola oil, and Canada has found success growing canola all along their southern border with the U.S. Lastly, we discuss how the process for converting canola oil into biodiesel is similar to how soybean oil is converted.

### 2.2.4.1 Current Production

The United States relies on importing canola to meet its demand. Figure 17 below shows the gap between what the U.S. is producing to domestic consumption. The difference between the two bar graphs is the amount of canola that must be imported to meet demand.

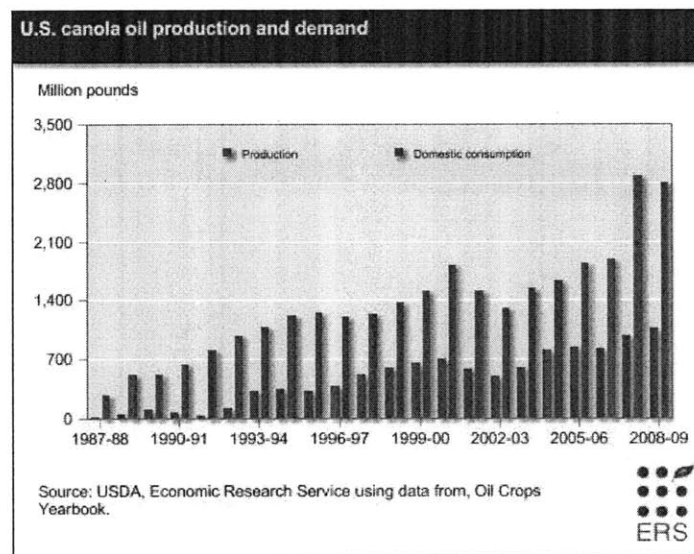


Figure 17. U.S. Canola Oil Production and Demand 1987-2009.  
(source: <http://www.ers.usda.gov/Briefing/SoybeansOilcrops/Canola.htm>)

Canola oil commands a higher price in the U.S. than soybean oil, so the amount of biodiesel created from soybean oil dwarfs the amount created from canola oil. The price difference is because canola oil demand has risen thanks to the food industry at a rate greater than soybean oil demand. In 2006, the amount of biodiesel created from soybean oil was ten times the amount created from canola oil (FAPRI, 2007). Also, in the U.S. cars run primarily on gasoline explaining why ethanol is the primary domestic biofuel. However, in Europe the majority of cars run on diesel fuel. Due to this, Europeans create more biodiesel than in the U.S. In Europe 65% of the biodiesel in 2008 was created from canola (USDA, 2010a).

## 2.2.4.2 Location of Crop and Yield

As Figure 19 below shows, in the United States, canola is primarily grown in North Dakota with some plantings in Montana as well. As previously stated, the United States relies on importing canola oil to meet its needs. Canada remains the largest importer of canola to the U.S. Figure 18 shows the Canadian provinces of Alberta, Saskatchewan, and Manitoba have a high percentage of canola crops in their southern regions. As the map shows, canola is primarily grown in areas with short growing seasons and dry weather.

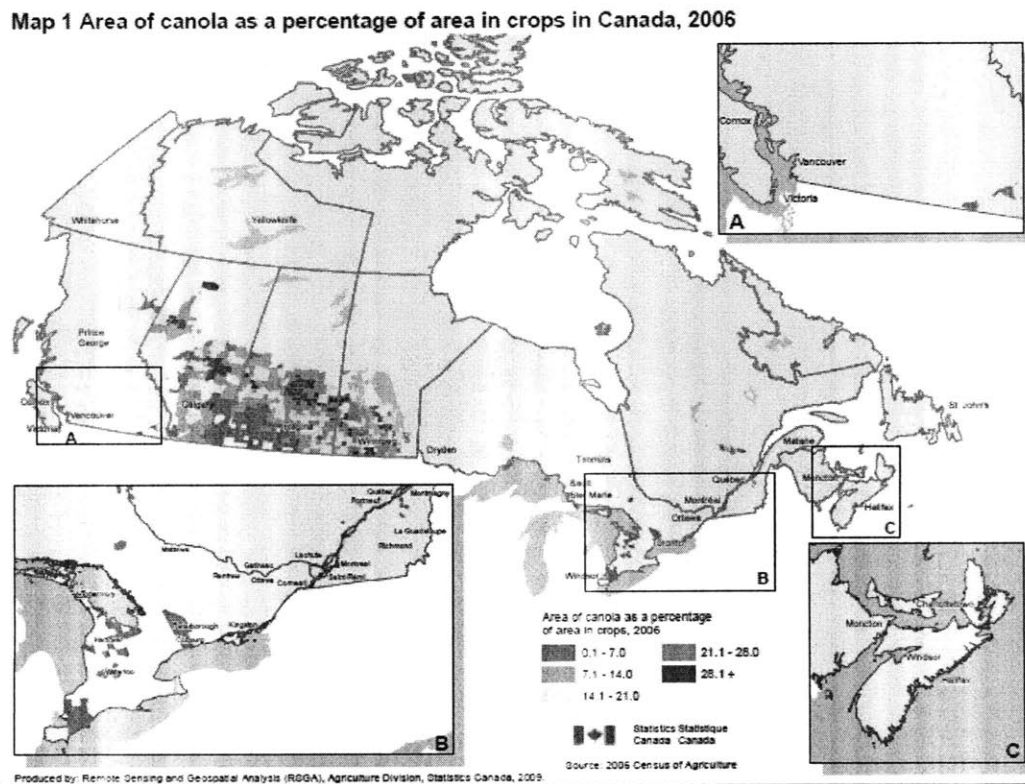
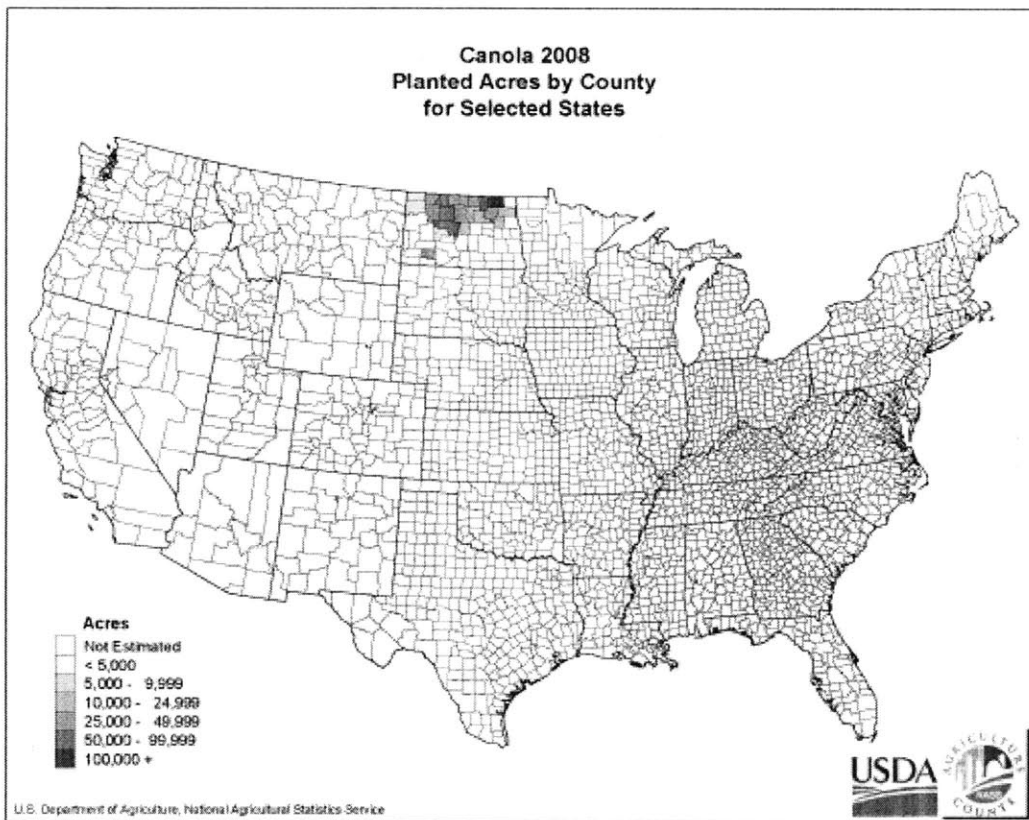


Figure 18. Area of Canola as a percentage of area in crops in Canada, 2006. (source: <http://www.statcan.gc.ca/cgi-bin/af-fdr.cgi?l=eng&t=Area%20of%20canola%20as%20a%20percentage%20of%20area%20in%20crops%20in%20Canada,%202006&loc=../m/10778m1-eng.pdf>)



**Figure 19. Canola Planted Acres by County for Selected States in 2008.**  
 (source: [http://www.nass.usda.gov/Charts\\_and\\_Maps/Crops\\_County/cn-pl.asp](http://www.nass.usda.gov/Charts_and_Maps/Crops_County/cn-pl.asp))

The FAPRI has also estimated yields in 2012, which is 1557 pounds per acre (2006). Canola oil can be extracted at 0.383 pounds per pound of canola. Using an estimate of 7.7 pounds of oil per gallon of biodiesel gives an estimate of 77 gallons of biodiesel per acre of harvested canola (FAPRI, 2006). This equates to a gasoline gallon energy equivalent of 78.6 gallons.

### **2.2.4.3 Biodiesel Production from Canola Oil**

Canola is crushed and the oil is extracted in a process similar to how oil is extracted from soybeans leaving canola oil and canola meal. The meal has uses outside of the biodiesel industry. Once the canola oil has been extracted, the transesterification process for this oil is very similar



to the process for converting soybean oil to biodiesel which is discussed in the soybean crop section.

### **2.2.5 Biodiesel Conclusions**

Similar to ethanol, there are many different feedstocks which can be used to produce biodiesel. Palm oil and coconut are very high yield, but they need a very unique environment in which to grow and are rarely grown in the U.S. Figure 20 shows that Rapeseed, of which canola is derived, has much higher biodiesel yield per hectare compared with soybean. Rapeseed is the main source of biodiesel feedstock in Europe, especially in Germany. However, it has not been widely accepted in the U.S., because farmers have little experience of growing canola. This is changing and farmers in Canada have been growing canola on a large scale. Canada was recorded as the top producer of rapeseed in 2008 while producing 12.6 million metric ton (Boland, 2010). Canada can be a stable source of rapeseed once companies in U.S. decided to produce biodiesel from rapeseed. Plantings in the U.S. are also increasing in North Dakota, as Figure 19 shows.

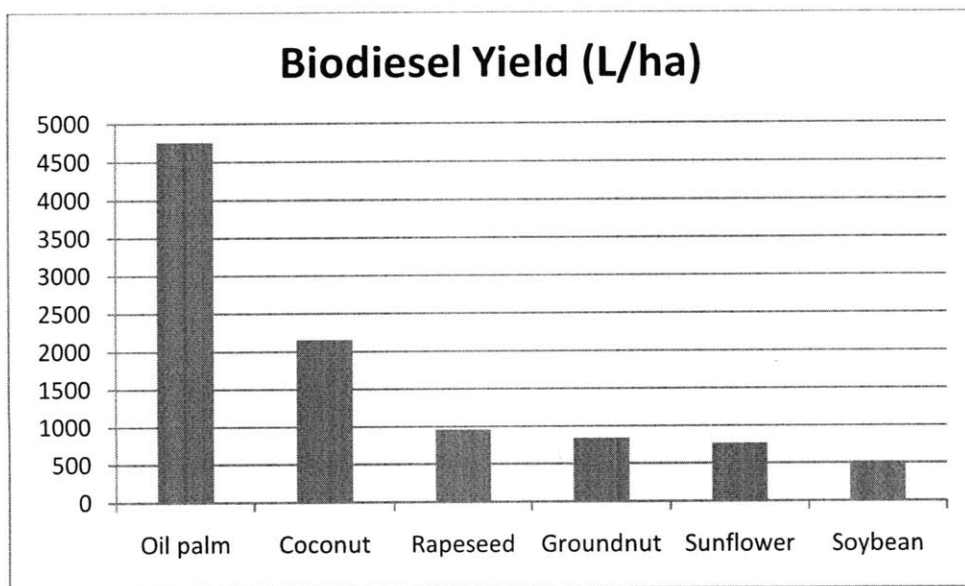


Figure 20. Yield of biodiesel from each feedstock.

## 2.3 Feedstock Conclusions

As this section has shown, the number of feedstock options is large and type of feedstock is diverse for the biofuels ethanol and biodiesel. The incumbent feedstocks for ethanol and biodiesel, corn and soybean, are dominant because they also have value as food crops. Getting farmers to produce crops with higher yields for conversion to biofuels can be difficult. Producing a food crop which doubles as a biofuel feedstock, such as corn or soybean, reduces risk for the farmer since they have a higher ability to sell the crop in case the biofuel market drops out. Compare this to producing a crop such as switchgrass which outside of growing switchgrass for conversion to ethanol, it has little value as a field crop. These types of tradeoffs which currently exist in the biofuel production industry are common in industries which are relatively new or experiencing rapid growth.

### 3                    **Biofuel Supply Chain Overview**

The supply chain for biofuel is described graphically in Figure 21 and is composed of five major stages: feedstock production, feedstock logistics, biofuel production, biofuel distribution, and biofuel enduse (Hilliard & Middleton, n.d.). The feedstock production stage includes issues including land availability, seeding, growing, yield, and the environmental impact of growing the feedstock. Beyond production, there is concern with using feedstocks that can also be used for food such as corn versus a non-edible feedstock such as switchgrass. However, the causality between the increasing use of feedstock and the rising world food price is not easily proven. The feedstock logistics stage includes all the issues related to moving feedstock from cropland to refineries. This stage is composed of four smaller steps, which are harvesting, storing, preprocessing, and transportation (Biomass Research and Development Board, 2008). The biofuel production stage is where the feedstock is converted into the biofuel. Improvements at this stage include increasing the yield of conversion for the biofuel from feedstock, developing byproducts that can be sold in addition to the fuel, optimizing conversion processes, and identifying best practices in related industries to use as benchmarks. Once achieved successfully, these improvements will make biofuel price competitive to that of gasoline. Issues in the biofuel distribution stage primarily occur because of geographical dislocation between the supply, which is mostly in the Midwest, and the demand, which are where population centers are on the West and East Coasts. One major issue is insufficient delivery capacity (Biomass Research and Development Board, 2008). The current biofuel distribution infrastructure, which includes storage and blending stations, rail cars and trucks, as well as the manpower for driving vehicles, are not sufficient to meet growing demand to deliver

biofuel. At the same time, some valves, seals, and gaskets in storage and blending stations are required to be replaced if a higher blend of biofuel may corrode them (Biomass Research and Development Board, 2008). The biofuel enduse stage focuses on how the consumers access the biofuel. Two significant levers in driving demand are cost efficiency and sustainability. Cost efficiency is the biggest issue, since the current biofuel costs more than its fossil fuel counterpart even with government subsidies. The sustainability of biofuel is being challenged by a significant amount of research. U.S. government and researchers who support biofuels need to further research and improve the sustainability of biofuel in terms of carbon footprint and net energy balance. Research must be performed to make sure higher biofuel blends do not damage existing vehicle engine parts at the end use stage of the supply chain.

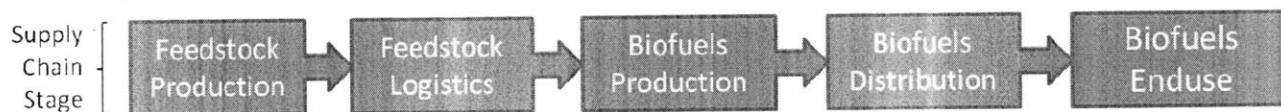


Figure 21. Five Stages of Biofuel Supply Chain. (source: Hilliard & Middleton, n.d.)

### 3.1 Feedstock Production

This stage consists of issues related to the feedstock itself and its production, such as research and development of feedstock, location of feedstock, seeding and fertilizing, and the costs of each step. Among these issues, research and development of feedstock and growing feedstock to increase the feedstock yield are agricultural or biochemical research issues and out of scope of this paper, therefore we will not delve into these issues. However, we state reasonable assumptions regarding future yields and the cost of feedstock.

### **3.1.1 Feedstock Production Supply Chain Decisions**

Many decisions exist for parties interested in producing feedstock for use in biofuels. The first decision is which feedstock to grow. For a crop such as switchgrass, there would be more financial risk than growing corn. In addition, issues such as where and how to grow that feedstock, along with how to improve yield and reduce cost, are all important decisions.

### **3.1.2 Feedstock Production Challenges**

There are a number of challenges involved in feedstock production. One major challenge for the industry is to minimize the price increase of food crops due to scarcity because the crop is being used for biofuel instead of food. Research conducted by the National Corn Growers Association argues that recent price increases of corn are not because of ethanol production, but due to rising oil prices (National Corn Growers Association, 2008). However, based on the basic supply and demand relationships, crop prices rise if the increase of crop consumption for biofuel production outpaces the increase of crop production. This can lead to increasing prices and food supply issues, especially in developing countries. Therefore, adequate forecasting of biofuel feedstock needs and crop production is necessary to identify and restrain possible food price increases. Using of 2<sup>nd</sup> and 3<sup>rd</sup> generation feedstock, which are non-food feedstock, can be an alternative to reduce the consumption of crops for biofuel production. Finding cropland and cost-efficient farming techniques for 2<sup>nd</sup> and 3<sup>rd</sup> generation feedstock are challenges that will always persist. On top of these efforts, farmers growing a crop they are not familiar with is another significant challenge.

Improving sustainability is also another challenge and many sustainable initiatives can actually reduce cost at the same time. For example, using water more efficiently will reduce the amount of water required for the crop. Developing an eco-friendly way to protect crops from insects or diseases would reduce use of chemicals, and it can also possibly lead to a cost reduction.

Improving the yield of a feedstock is another major challenge, because this is directly related to unit cost of feedstock.

An assessment of the environmental impact of feedstock cultivation of each feedstock is another challenge to be addressed. Environmental implications such as effect of feedstock cultivation on the quality of soil, water, and air should be analyzed because environmental concerns are the main reasons why biofuel is produced in the first place. Improving the net energy balance, which is relationship of maximizing energy output and minimizing the amount of energy input, and net carbon reduction of growing feedstock is also a critical issue.

### **3.2 Feedstock Logistics**

The feedstock logistics stage contains all steps required in delivering feedstock from the field to the conversion facility. In the case of cellulosic ethanol, this logistics cost is one of the major cost drivers and constitutes as much as 20% to the finished product cost. This stage is composed of four main elements (Biomass Research and Development Board, 2008):

- a. Harvesting and collecting - removing feedstock from the area of growth

- b. Storage - providing steady supply of feedstock without spoilage (activities include: where to locate storage facilities, what preparation steps are required of the feedstock before placed into storage, and other inventory issues)
- c. Preprocessing and grinding - transforming feedstock to a more energy-dense form for efficient transportation, and preprocessing feedstock to facilitate the conversion process
- d. Delivery & transportation - moving feedstock from the farm or forests to the refinery in a cost-efficient manner

The cost incurred in this stage is one of the major cost drivers. Despite the significance of logistics in the whole biofuel supply chain, this area has received minimal governmental attention.

Two goals of feedstock logistics are to ensure stable supply of quality feedstock over time and transport feedstock in a cost efficient manner. However, these two goals are not easy to achieve because of the nature of feedstock and its production. First of all, feedstock is normally harvested during a specific season, once a year, and the feedstock needs to be stored and preserved to provide steady supply throughout the course of the year, increasing storage and holding costs. Moreover, year-to-year production naturally varies, and other agricultural irregularities, such as crop rotation, make producing a predictable amount of supply difficult.

Solutions to these logistics issues can be divided into two categories; the industry can either improve the efficiency of existing logistics system or develop new technologies. To operate the existing logistics system more efficiently, the design of feedstock collection, storage, preprocessing, and delivery systems should be optimized based on the feedstock type, geographical factors, available storage and preprocess facilities, and available transportation

means. This optimization of the existing supply chain should be dynamic; it should be updated and re-optimized according to the changing environment. Developing new technologies means devising new methods for biofuel logistics. For example, moving feedstock in liquid or slurry form through a pipeline may represent a way to reduce transportation and labor cost. However, water accumulates in pipelines affecting the fuel, and high amounts of ethanol in a pipeline can tend to lead to corrosion and stress corrosion cracking. New methods and equipments are continually devised and tested by industry and academia to enhance the cost-efficiency of feedstock supply (Biomass Research and Development Board, 2008).

### **3.2.1 Feedstock Logistics Supply Chain Decisions**

This stage comprises of activities required to move feedstock from cropland to bio-refineries. Therefore the first decision to be made is which equipment and technique is used to harvest the feedstock. After harvesting, feedstock can be stored and preprocessed to increase its energy density. Therefore, the number and location of storage facilities and preprocessing facilities is an important decision. Preprocessing and storage methods are also important decisions because it can affect the mode of transportation required to move feedstock and also the cost of delivery. For example, transporting a baled feedstock can use an entirely different truck than transporting pelletized feedstock. In addition, the mode of transportation is another important decision.

### **3.2.2 Feedstock Logistics Challenges**

The role of this stage in the supply chain is supplying feedstock to bio-refineries. Therefore, the first and foremost challenge in this stage is to provide reliable and consistent supply of quality feedstock over time. The total production of crops naturally fluctuates and crops are



harvested in a specific period of the year. Second, numerous variables affect the crop yield of the year, so the yield fluctuates from year to year. In addition, there are other factors, such as crop rotation, which agitate stable crop production. These issues make preserving feedstock throughout the year and maintaining a stable supply of feedstock a challenge.

Finding increasingly more effective preprocessing methods is another challenge, because effective preprocessing the feedstock significantly contributes to cost reductions by delivering feedstock in more energy-dense forms or even enabling new delivery schemes. For example, once constructed, a pipeline is by far the cheapest method to deliver feedstock to refinery, and if farmers could change feedstock into a slurry or liquid form at a moderate scale, it would enable the adoption of feedstock transportation via pipeline.

Optimizing the delivery network is the challenge which can provide the quickest benefit if properly conducted. While almost 50% of corn is shipped by barges, 98% of corn for ethanol production is delivered by truck, which is the most expensive mode of transportation (USDA, 2007). Applying networking techniques, such as comparing a point to point system with a hub and spoke system, may expose other ways to reduce cost.

Innovative, disruptive technologies and logistics strategies may come along as well. For example, collecting agricultural residue on the harvesting field can provide another ample source of feedstock, which in the past was burnt or left to decompose in the field. Currently, a great deal of research is being undertaken to improve harvesting feedstock by members of industry and academia.

Preprocessing feedstock at the point of harvest or in transit, could potentially lead to the reduction of processing stages at the conversion plant and reduce cost, leading to a more efficient next stage, biofuel production.

### **3.3 Biofuel Production**

This stage includes all the issues related to transformation of the preprocessed feedstock into biofuel. Currently production technologies are not cost-efficient enough for biofuel to compete effectively in the marketplace with petroleum based fuels, even though research and development on developing ethanol and biodiesel has been reducing estimated conversion costs. Figure 22 shows how ethanol conversion costs have decreased over time. There is promising research emerging to assist in the conversion process. For example, scientists are looking into how to minimize 'recalcitrance', the kinetic phenomena in which the rate of cellulose digestion slows during extended reaction, which is one of the key barriers (Himmel, Vinzant, Bower, & Jechura, 2005). This phenomenon occurs because the plant fiber resists breaking down into sugar intermediates during the reaction. Another key focus area researchers are investigating is improved understanding of how plant material breaks down thermally. Catalysis, or rate of conversion in response to a catalyst, is another area with significant potential to improve the chemical and thermo-chemical conversion processes. While there are many technologies on the horizon that will increase the conversion yield from feedstock to biofuel, they are outside the scope of our analysis. We will assume similar increases in conversion yields to what has happened historically (Biomass Research and Development Board, 2008).

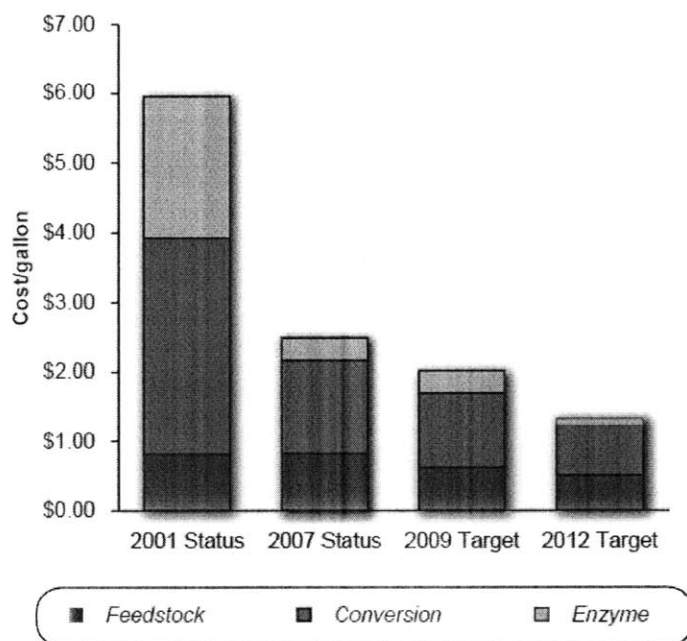


Figure 22. 2012 cost competitive target. (source: Biomass Multi-Year Program Plan: December 2009, DOE EERE)

### 3.3.1 Biofuel Production Supply Chain Decisions

The first supply chain decision in this stage is deciding what the conversion plant network looks like. An adequate number of plants are needed to ensure enough conversion capacity to meet the biofuel demand. Whether to have a large plant or multiple small ones is another decision to be made. As plants grow in size, the amount of energy required to get feedstock to the plant increases because the feedstock will be brought in from further away. The refinery location relative to farms is also an important supply chain decision. These decisions can be helped by adopting optimization techniques.

### 3.3.2 Biofuel Production Challenges

Challenges in this stage are conversion, mostly chemistry-related, issues. First of all, increasing the conversion yield is the most significant challenge because it will reduce the cost of biofuel, which will act to widen the customer base of biofuel. There are number of challenges currently being researched. Improving understanding of the ‘recalcitrance’ phenomenon and minimizing or even eliminating this is one of the most significant milestones in increasing yield of cellulosic ethanol production. Recalcitrance is the natural resistance of plant cell walls to microbial and enzymatic deconstruction (Himmel et al., 2007). Another important mission is to improve understanding of the thermal breakdown of materials in the conversion tank. In addition, there is a potential improvement in the conversion process by developing advanced catalysts. Constant advancement in knowledge of microbes and enzymes is also required to improve conversion yields.

Second, developing technologies that enable production of economically beneficial co-products is another major challenge. This would enable the refinery to sell fuel at a lower price due to the additional profit made on the sale of the co-products.

Third, finding best practices and innovations from related industries, such as petroleum refining, chemical manufacturing and bioengineering, would also benefit the biofuel production. Ideas and techniques learnt from related industries can be leveraged to enhance biofuel production.

### **3.4 Biofuel Distribution**

The distribution stage comprises issues of delivering fuel from a refinery to end customers. For delivery, a network of trucks, trains, barges, and, possibly in the long term, pipelines can be utilized. In addition, blending and storage stations are required to mix biofuel with traditional, petroleum based fuel.

One problem in the distribution of biofuel is regional dislocation of supply and demand. While most biofuels are produced in the Midwest and other rural areas, consumers of the fuel are heavily concentrated on the West and East coasts. As a result, refined biofuel typically has to be moved over a significant distance.

The production of biofuel is expected to increase yearly. However, the current capacity of transportation network is not enough to effectively connect the supply and demand of biofuel (Biomass Research and Development Board, 2008). Therefore, increasing the delivery capacity is required along with finding the more cost-efficient way to deliver. At the same time, the number of blending and storage stations must match increased production and demand of biofuels (Biomass Research and Development Board, 2008).

#### **3.4.1 Biofuel Distribution Supply Chain Decisions**

The purpose of this stage is to deliver blended biofuel to the end customers. Therefore where and how many blending stations to install are major decisions in this stage. Deciding which mode of transportation used to distribute the fuel is another major issue. The final mix, or proportion of biofuel to petroleum based fuel, of the blend is also a major decision, because it will directly affect the size of the biofuel market. If the adoption of E85, 85% ethanol, capable

engines increases rapidly, a great deal of ethanol will be required very quickly since the current blends are mostly E10, 10% ethanol. Also, locating where to blend the biofuel with petrochemical fuel is another important decision. It can be blended either at the petrochemical refinery or at a storage tank before being shipped to the point of sale to the end customers.

### **3.4.2 Biofuel Distribution Challenges**

One major challenge in this stage is the geographical dislocation between supply, concentrated in the Midwest, and demand, which is primarily on the West and East Coasts. This not only increases the cost of delivery but also makes the delivery complicated. However, this physical dislocation will always exist, since there are few biofuel refineries outside of the Midwest. Therefore, ensuring stable delivery in a cost-effective manner is essential.

Another major challenge is to ensure enough capacity to meet increasing biofuel demand. Above all, the number of blending stations need grow with demand. In addition, biofuel transportation capacity must be expanded; the current number of rail cars and hazmat drivers is not sufficient to meet increasing need. It is estimated that there will be a 111,000 driver shortfall in 2014 (Global Insight, Inc., 2005). While securing more rail cars and truck drivers, other methods of distribution can be analyzed to see if they are cost effective, such as pipelines. However, high amounts of ethanol can tend to lead to corrosion so a pipeline may represent a cheap method to transport biofuel in the future once issues mitigating its corrosive effects on pipelines.

Ensuring safe delivery and use of high biofuel blends is another challenge. High blends can corrode some parts of existing blending stations, such as valves, seals and gaskets, and these

blends can also deteriorate some components of car engines (Biomass Research and Development Board, 2008). Researchers have to develop ways to ensure chemical stability of biofuel during the delivery and in the blending station. At the same time, cost efficient ways to replace existing component in car engines to ones durable to higher blend should be developed, and this would lower barriers for people to adopt higher blends.

### **3.5 Biofuel End Use**

The end use stage is the point of sale where customers purchase biofuels for use in their vehicles. A critical issue here is how to facilitate the adoption of biofuels by end customers in place of the traditional petrochemical fuel, which they are accustomed to. The first and foremost driver of biofuel demand is fuel price, and this price can be made competitive with alternatives either by efficient processes or increasing government subsidies for biofuel. Government subsidies are not a sustainable way to support biofuels, so it is imperative to produce biofuels inexpensively such that they can be competitive without subsidies. In addition, making biofuel blends with existing fossil fuels compatible with existing car engines is also important. Increasing the ratio of biofuel in the blends also can affect the demand for biofuels. As previously mentioned, increases in the compatibility of engines in new cars, or refitted engines, with E85 (85% ethanol, 15% gasoline) blends will cause more ethanol demand. To ensure the compatibility of intermediate blends (blends with ethanol content higher than 10%) with regular vehicles, understanding the impact of new blends on emissions must be examined. Moreover, studying driving performance and materials compatibility, such as plastic seals and valves, with new biofuel blends also need to be assessed (Biomass Research and Development Board, 2008).

### **3.5.1 Biofuel End Use Supply Chain Decisions**

In this stage, the capacity and location of pumps are major supply chain decisions. For example, the fuel could get sold to gas stations for sale or it could be sold to companies which operate a fleet of vehicles. Each consumer has different performance and delivery expectations.

### **3.5.2 Biofuel End Use Challenges**

The biggest challenge is how to market biofuel to the greater population, increasing the pull of demand from the consumer. The most straight forward way is to reduce the price of biofuel. Another way to increase demand is to increase the portion of biofuel in the blends used by end customer.

High biofuel concentrations in pumps and tanks have the potential to erode plastics quicker than normal petrochemical fuels. (Biomass Research and Development Board, 2008) Research must be performed so that plastic seals can resist damage due to prolonged biofuel contact. Since high amounts of ethanol can tend to lead to corrosion and stress corrosion cracking.



## **4 Cost Analysis for Ethanol Production with Switchgrass**

Since switchgrass is recognized as a feedstock for future ethanol production, we analyze the current cost structure of switchgrass. The first section details issues specific to the switchgrass supply chain, and the second section will examine the cost breakdown of what is involved in creating a gallon of ethanol from switchgrass as a feedstock.

### **4.1 Switchgrass Supply Chain Issues**

The supply chain for switchgrass follows the biofuel supply chain given in section three above. However, the first two stages, feedstock production and feedstock logistics need to be examined in further detail focusing on switchgrass to provide a tailored cost estimate. Once ethanol has been converted from the feedstock, it can be distributed the same as corn-derived ethanol, and the end use will also be the same as in section three. Therefore, this section will focus on feedstock production and feedstock logistics specific to switchgrass.

#### **4.1.1 Switchgrass Production**

Switchgrass is a non-edible feedstock adaptable to marginal lands. Therefore, it can use land which is not currently used for food production, minimizing any impact of ethanol production on the world food supply. Moreover, growing switchgrass has aspects which are beneficial to the environment. Bransby in 2010 outlines the benefits, which come about mainly because of the perenniality of switchgrass. First, switchgrass contributes much more to prevent soil erosion compared with annual crops. Second, switchgrass requires less tillage, so soil carbons are preserved better. Third, switchgrass requires less toxic chemicals. Chemicals such as herbicides

are intensively required in the seeding and early growth stage of crops, and since switchgrass is perennial, it will not need as many herbicides (Bransby, 2010). As previously mentioned, researchers at Metabolix Inc. have recently developed new techniques to produce biodegradable plastics out of switchgrass, potentially leading to reduction in the use of non-environment-friendly plastic. This also improves the economic viability of the crop since adding a plastic byproduct genetically can increase the crop's value.

**Table 1. Projected Yield of Switchgrass. (source: Sokhansanj et al., 2009)**

Projected increase in the yield of switchgrass			
US Production region	Baseline yield (2004) (Mg ha <sup>-1</sup> )	Projected 2030	Times Increased
North-East	10.9	16.0	1.47
Appalachia	13.0	46.4	3.57
Corn Belt	13.4	28.8	2.15
Lake State	10.7	15.8	1.48
South-East	12.3	43.7	3.55
Southern Plains	9.6	34.2	3.56
Northern Plains	7.8	11.4	1.46

The biggest challenge for the switchgrass production is to reduce cost to grow and still increasing the yield per hectare. According to McLaughlin and Kzos (2005), the overall U.S. average yield of switchgrass is 11.2 Mg ha<sup>-1</sup>, ranging from 4.5 Mg ha<sup>-1</sup> in the Northern Plains to 23.0 Mg ha<sup>-1</sup> in Alabama. McLaughlin and Kzos expect the yield of switchgrass in U.S. to increase twice or three times in the long term. In another study by Sokhansanj et al. in 2009 finds similar yields as shown in Table 1. The Appalachian, South-East, and Southern Plains regions of the United States are areas where the yields of switchgrass are expected to increase dramatically.

Another issue in the production of switchgrass is geographical dislocation of available cropland for switchgrass production and land with higher switchgrass yield. Figure 23 below shows where switchgrass grows better graphically. Switchgrass grows well in traditional Corn Belt states, which are Indiana, Illinois, Iowa, and Kentucky. Appalachian states such as West Virginia also show potentially high yields for switchgrass farming. Arkansas and northern Louisiana also seem to be suitable for switchgrass production. Figure 9 in chapter 2 shows the land available for use in growing switchgrass. North Dakota, South Dakota, western Minnesota, Kansas, and northern Texas have land available for switchgrass production at costs that could make switchgrass grown for ethanol production competitive. A comparison of these two figures, Figure 9 and Figure 23, shows the clear tradeoff between the switchgrass yield and the land available for switchgrass production. The land that is available will not provide as high of yields as land that is already being used to grow food crops such as corn and soybeans.

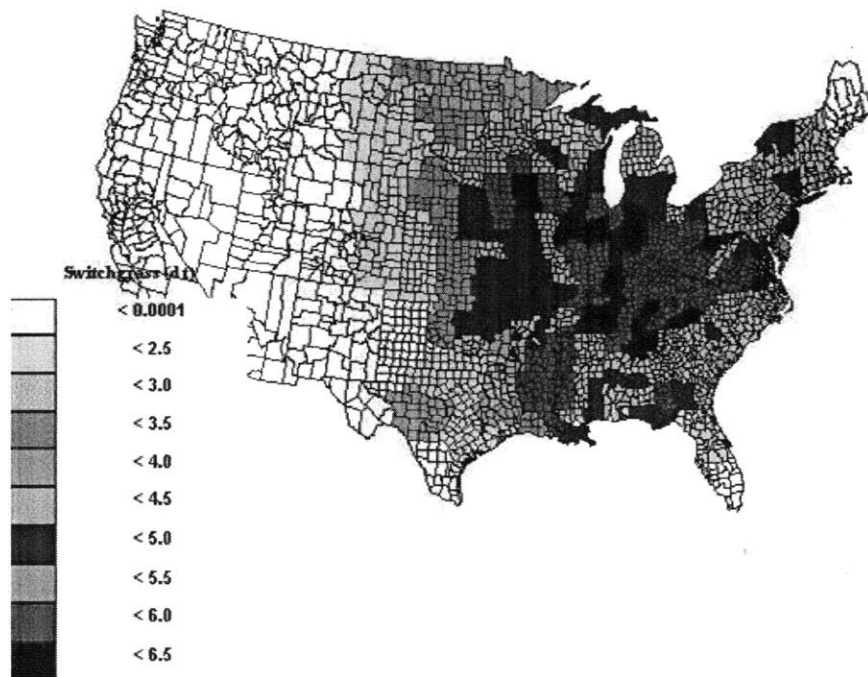


Figure 23. Expected Switchgrass Harvest Yields by Region. (dry ton per acre) in 2005 (source: Sungrant Bioweb)

#### 4.1.2 Switchgrass Harvesting

Switchgrass grows from early spring (May-June) to late fall (October-November). Farmers can harvest this plant at any time during the year, and they can diversify their harvest strategies by changing the frequency and time of harvest. These two levers affect the yield per area of land. While a great deal of research on yield has been done in different regions, most of them conclude that harvesting once at the end of the season would lead to the maximum biomass yield and sustainable production of switchgrass (Sokhansanj et al., 2009). The frequency of harvest changes the material composition in the switchgrass, such as ash content (Blade Energy Crops, 2008).

Harvest handling operations for switchgrass are similar to those for other grasses. Because switchgrass has a well-developed root system, harvesters can easily gather them with cutting devices. Currently, there are two trends evolving in the collection of switchgrass. The first method is the 'single-pass harvesting'. This attempts to handle multiple stages of harvesting with one piece of equipment. For example, mowing and conditioning can be done at the same time by using enhanced baling machine. The conditioning job accelerates the drying by allowing moisture to more easily leave the grass. A second trend evolving is to make the output of harvesting as large and dense as possible so the harvester can minimize the number of trips between the field and the storage (Sokhansanj et al. 2009).

Figure 24 shows the available options for switchgrass harvesting. The activities within the box are stages that can be performed with a single piece of equipment. Mowing and conditioning are the first stages of switchgrass harvesting. A mower-conditioner can perform these two activities almost simultaneously by crushing and crimping stems of plants in the machine on the

field. Figure 25 shows this type of machine. The mower-conditioner can move as fast as normal mower, but requires almost twice as much power.

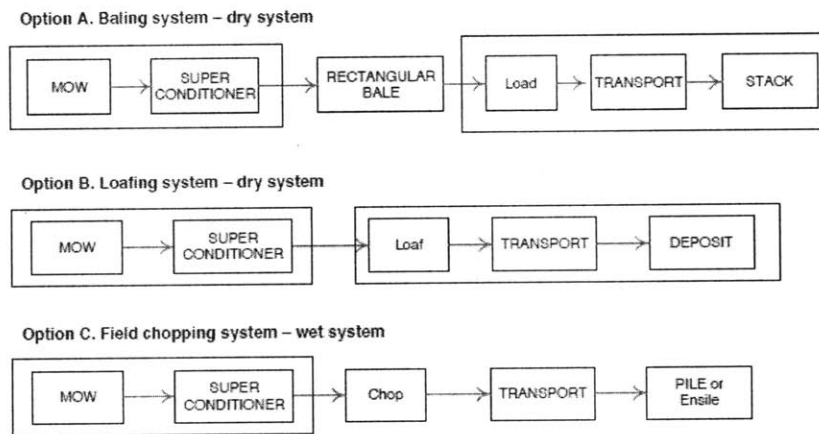


Figure 24. Advanced Options for Harvest and Collection of Switchgrass. (source: Sokhansanj et al., 2009)

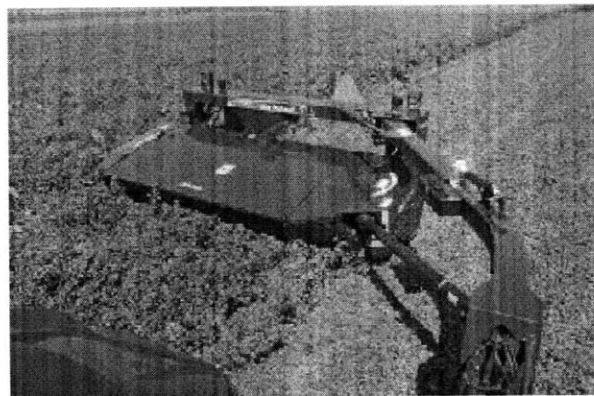


Figure 25. Automatic Mower. (source: <http://www.efarming.com.au/NewProducts/machinery/08/01/2009/1354/cleaner-cut-less-downtime-with-discbine-disc-mower-conditioner-advanced-mowmax-modular-cutterbar.html>)

Baling is one of the most common harvesting techniques. There are two types of common bales – round and rectangular. While round bales are more popular in the U.S., it is assumed that rectangular bales are more suitable for biomass collection. Round bales tend to deform more easily when made of switchgrass, and it is difficult to load a truck with misshaped bales

(Sokhansanj et al., 2009). Moreover, an uneven round bale makes the de-baling operation difficult. While a large, rectangular bale sided 1.2m x 1.2m x 2.4m is popular, the density of smaller bales (0.9m x 1.2m x 2.4m) is about 10% higher. The density of bales ranges from 140 to 180 kg m<sup>-3</sup> with an average density of 163 kg m<sup>-3</sup> (Sokhansanj et al., 2009).

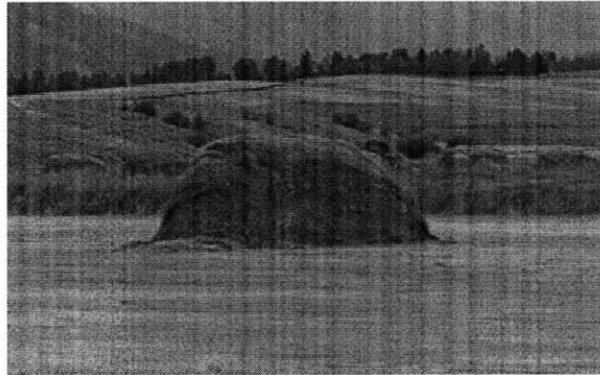


Figure 26. Grass Loaf. (source:

<http://www.wunderground.com/wximage/viewsingleimage.html?mode=singleimage&handle=funhawg&number=1677&print=1>)

Loafing is another advanced technique to collect biomass. A switchgrass loaf is made out of dry biomass, which has moisture content of less than 15%. The average loaf is about 2.4 m wide, 6m long, and 3.6 m high. During the stacking, the roof of the loafer exerts a pressure to the biomass under the roof and increases the density up to 80 kg m<sup>-3</sup> (Sokhansanj et al., 2009). Once the loafer is filled with switchgrass, the loaf is transported to the storage area.

Chopping is a technique to breakdown switchgrass into smaller pieces (25~55mm). If chopping is done after the moisture content drops to less than 15%, it is called dry chop. Otherwise, it is called wet chop. Wet chop must be dried before taken to storage, otherwise the grass runs the risk of growing mold and mildew. There is usually a forage wagon traveling along the forage harvester, which collects the chopped material.

Table 2. Cost Comparison of Baling, Loafing, and Chopping. (source: USDOE, <http://programreview.biomass.govtools.us/%5Cdocuments%5C6615eda9-baca-4e0d-ad94-6994d550af59.ppt>)

		Transport options (\$/dT)		
		Bales	Grinds	Chops
Collection		\$ 13.70	\$ 15.45	\$ 14.26
	Format	\$/dT	Overall cost \$/dT	
Switch-grass	Baling	\$ 28.17	\$ 43.93	\$ 45.94
	Loafing	\$ 23.31		\$ 41.07
	Chopping	\$ 40.67		\$ 57.07

Table 2 shows the costs per dry ton (dT) for different collection and transportation options. Out of three harvesting option listed above, the loafing option provides the best delivered cost at the refinery. While the density of bailed switchgrass is higher than that of loafing, bailing required additional stacking step which makes it cost more than loafing (Sokhansanj, Perlack, & Turhollow, 2005). This is because feedstock is stacked on a loafer directly, while bales are first baled on the ground and stacked on a flatbed truck or a front-end bale grabber.

#### 4.1.3 Switchgrass Storage

To ensure the stable supply of feedstock throughout the year, storage of feedstock is essential. As mentioned above, the number and location of storage facilities should be determined based on optimization using constraints such as available capital and regulatory limits. One of the storage challenges is minimizing loss of feedstock. According to research by Shinner et al. in 2006, dry bales stored outdoors showed significantly more matter loss than bales stored indoors (Shinners, Boettcher, Muck, Weimer & Casler, 2006). In their experiment they stored dry bales outdoors and indoors for 9 and 11 months with different storage methods. For dry bales stored outdoors, they found 3.4% dry matter loss for bales wrapped with plastic film, 7.7% with net wrap, 8.3% with plastic twine, and 14.9% with sisal twine. Bales stored indoors without any wrap showed

average dry matter loss of only 3%. Dry bales ensiled in a tube of plastic film showed dry matter loss of 1.1% (Shinners, Boettcher, Muck, Weimer & Casler, 2006). However, building a storage facility for indoor storage and ensiling bales requires an additional cost. Therefore, the tradeoff between cost and dry matter loss should be analyzed before choosing the storage method.

#### **4.1.4 Switchgrass Preprocessing**

Volume and weight are two factors that limit the size of loads on vehicles. In the case of unprocessed switchgrass, the volume is by far more significant limiting factor. According to U.S. Department of Transportation regulations, the weight limit of a truck is 80,000 lbs, which is about 36,300 kg (United States Department of Transportation, n.d.). In the case of switchgrass, the densest form is when it has been pelletized, which has a density of  $700 \text{ kg m}^{-3}$ . If we divide the weight limit with the pellet density, it gives a volume of  $51 \text{ m}^3$ , which is far bigger than the volume of what a truck typically can transport. This proves that the weight of the feedstock of a full truck load is inherently lower than the legal limits for load weights, and that volume is the limiting factor. Therefore, decreasing volume by increasing density through preprocessing enables one to increase the weight and energy density of feedstock per truck. This increases the amount of energy moved in one trip, and decreases the number of trips to transport large amounts of feedstock and in turn, reduces the transport cost.

As shown below in Table 3, the density of chopped switchgrass averages  $70 \text{ kg m}^{-3}$ , while that of baled dry biomass is  $163 \text{ kg m}^{-3}$  (Sokhansanj et al, 2009). If the chopped feedstock is ground further and filled into a container, the density increases to  $120 \text{ kg m}^{-3}$ . If the feedstock holder is vibrated, the density can rise up to  $200 \text{ kg m}^{-3}$ . To improve the density further, the biomass needs to be mechanically compacted.



Table 3. Bulk Density of Switchgrass. (source: Sokhansanj et al, 2009)

Bulk density of switchgrass		
Form of biomass	Shape and size characteristics	Density (kg m <sup>-3</sup> )
Chopped biomass	20~40mm long	60-80
Ground particles	1.5 mm loose fill	120
Baled biomass	Round or large squares	140-180
Ground and packed particles	1.5 mm pack fill with tapping	200
Briquetts	32 mm diameter x 25 mm thick	350
Cubes	33mm x 33mm cross section	400
Pellets	6.24 mm diameter	500-700

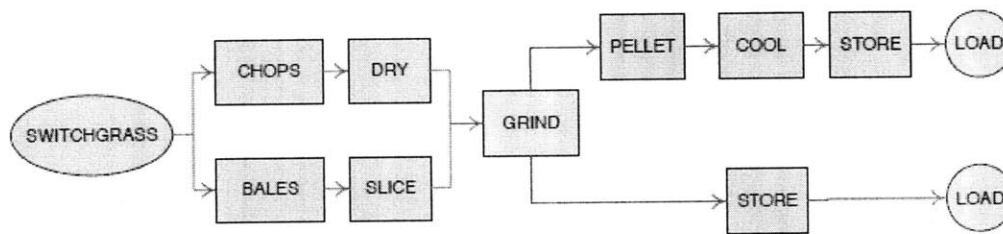


Figure 27. Flow Diagram for Densification of Biomass to Pellets or to Small Particles. (source: Sokhansanj et al, 2009)

Figure 27 is a schematic diagram of two preprocessing options. Incoming biomass has usually been chopped or baled. Baled biomass has to be sliced first. Chopped switchgrass must be dried if is wet. 'Dry' means that the moisture contents should be lower than 15%. Once dry, biomass is ground into particles with an average size of 1.5 mm. After grinding, the density of 1mm ground switchgrass is approximately 120 kg m<sup>-3</sup> (Sokhansanj et al., 2009). While this state is suitable for shipment of short distances, it is advantageous to compress grounds further into pellets (Sokhansanj et al., 2009). After pelletization, the average density of switchgrass is approximately 600 kg m<sup>-3</sup> as shown above in Table 3. According to the research of Mani, Sokhansanj, Bi, and Turhollow, the pelletizing cost for switchgrass amounts to \$10 - \$18 Mg<sup>-1</sup> according to the size of pelletization facility (Mani, Sokhansanj, Bi, & Turhollow, 2006). Below

Figure 28, taken from the same article by Mani et al., shows a schematic for the activities involved in pelletizing switchgrass. First the material comes in, is dried, pelletized, screened, and then finally stored. Pellet screening is performed to eliminate oversized pellets or undersized pellets called “fines” from the batch of pellets so that the final product is all of uniform size.

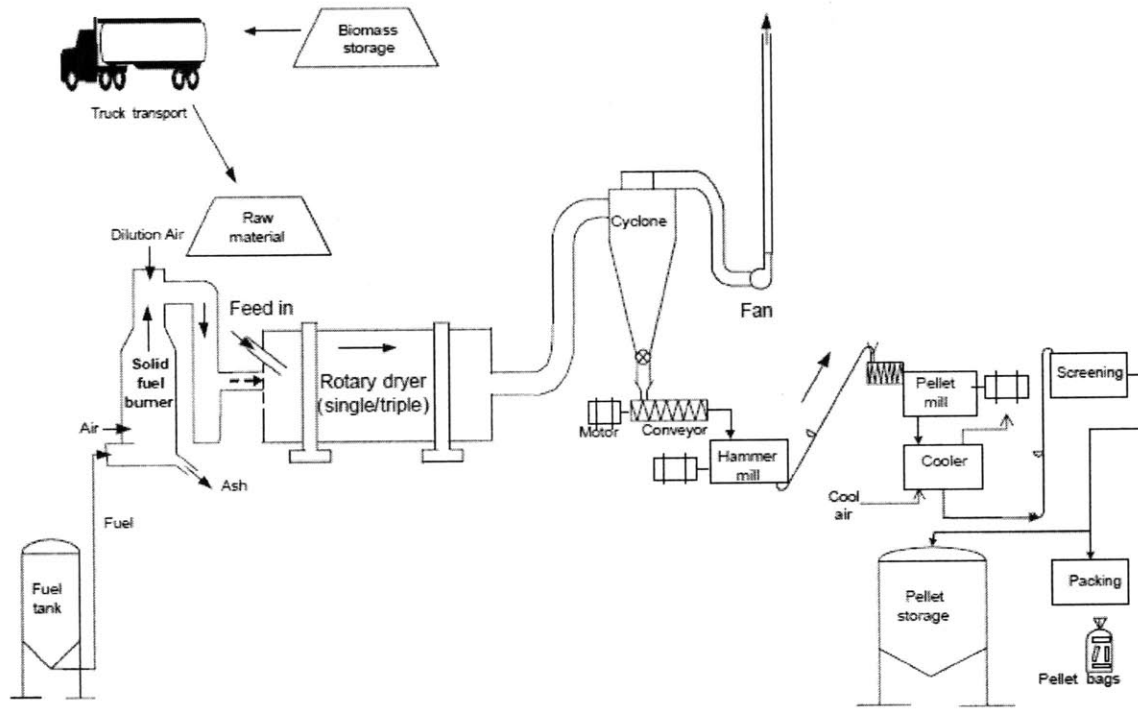


Figure 28. Schematic Layout of a Typical Biomass Pelletizing Plant. (source: Mani et al., 2006)

#### 4.1.5 Switchgrass Transport

There are four potential transport options for switchgrass: truck, train, barge, and pipeline. Trucks are the most convenient means for loading and unloading of biomass and are also the cheapest mode for local transportation. Shipping via train can be cheaper than truck when the distance is longer than 160 km (Sokhansanj et al, 2009). Shipping via barge is an unrealistic

option for local transportation in the Midwest, but could be viable for exporting ethanol to other countries or shipping along the U.S. coasts. Using a pipeline is an attractive transportation option if the technology is developed enough to move switchgrass slurry through the pipe. At the same time, the utilization of the pipes should be high enough to economically rationalize the high initial investment cost of a pipeline system. As previously mentioned, ethanol also has shown to be very corrosive in pipelines, and it also has problems with water accumulating in the fuel.

## **4.2 Economic Analysis of Switchgrass as a Feedstock for Ethanol**

The previous section showed information specific to the switchgrass supply chain from field to refinery. In this section we discuss the costs associated with planting, cultivation, harvest, storage, transportation, and conversion to ethanol. Two different plant sizes are examined. The first plant consumes 2000 Mg worth of switchgrass a day, and the second uses 5000 Mg. Total yearly ethanol production is 60 and 150 million gallons for the 2000 Mg and 5000 Mg plant respectively, under the assumption that these plants produce ethanol for 300 days a year. The amount of switchgrass needed on a daily basis affects the average distance the feedstock travels from farm to refinery. A large refinery will need a larger amount of feedstock daily so it will exhaust the local supply of switchgrass more quickly than the smaller refinery. Lastly, three different ways to harvest switchgrass are examined. Baled, ground, and pelletized switchgrass will all be examined. In the following sections, each process will be converted into the cost per gallon which it takes to perform the task. Basic assumptions are that the yield per acre is 10 Mg Ha<sup>-1</sup> and that one kilogram of switchgrass can be converted into .38 liters of ethanol (Schemer et al., 2007).

#### 4.2.1 Planting and Cultivation

According to Sokhansanj et al., for a switchgrass field with a yield of 10 Mg/hectare, the cost to do all planting and cultivation is \$41.50 per Mg. As shown above in Table 1 from the beginning of this chapter, the yield of switchgrass per acre is expected to increase over time as more mature technology and best practices emerge, so in the future, we are hopeful that it is reduced. As noted above, based on the paper of Schmer et al. (2007), we assumed a conversion rate of switchgrass to ethanol set at .38 liters  $\text{kg}^{-1}$ . This is same as 100.4 gallons  $\text{Mg}^{-1}$ . Therefore, The cost per gallon of planting and cultivation is \$0.41 on a farm with a 10 Mg/Hectare yield (Sokhansanj et al., 2009).

#### 4.2.2 Harvest and Storage

We examine two ways to harvest the switchgrass: baling and loafing. When switchgrass is baled, it is able to be stored or loaded onto trucks for shipment to the refinery without further processing on the farm. Loafing requires another step, and our analysis uses loafing for switchgrass that is ground or pelletized at the farm. Sokhansanj et al. estimate that baling costs \$23.72 Mg/Hectare or \$0.24 per gallon of ethanol, while loafing costs \$17.50 Mg/Hectare or \$0.17 per gallon (2009). The switchgrass that is loafed is then ground or pelletized.

Pelletizing switchgrass estimates come in at \$17.97 / Mg, or \$0.18 per gallon (Sokhansanj et al, 2009). During the pelleting process, the switchgrass is ground, so eliminating the steps unique to pelletizing costs and we can derive the cost to grind the switchgrass. We estimate it will cost \$10.10 per Mg or \$0.10 per gallon of ethanol to grind switchgrass. In the case where the switchgrass is transported in the ground state, we apply this amount to the

feedstock at the farm. However, if the feedstock is transported in baled form, we apply this cost to grind the feedstock at the refinery, once it has been delivered. The advantage of grinding at the farm is that by increasing the energy density of the feedstock, the transportation costs are reduced. This is because fewer trucks are needed to transport the feedstock from farm to refinery. As shown in Table 3, Bulk Density of Feedstock, the most energy dense form of feedstock is pellets. The cost advantage for pelletizing is larger as the distance traveled from farm to refinery increases.

#### **4.2.3 Transportation from Farm to Refinery**

For this analysis, we use the same guidelines provided by Sokhansanj (2009) by assuming the area surrounding the refinery has 25 percent of farmland dedicated to switchgrass production. Using these assumptions, the maximum distance for a 2000 Mg per day facility is 17 miles and for a 5000 Mg per day facility it is 27 miles. This translates into an average load distance of 11.4 miles and 18.1 miles respectively. We created a linear programming model which supposes the farmer uses a third party trucking company to haul his product to the refinery.

Baled switchgrass is difficult to load and unload compared to grinded or pelletized switchgrass. Because of this we used a time of an hour each for loading and unloading baled switchgrass versus a half hour for grinded or pelleted switchgrass because they have better bulk handling characteristics. Also, we assumed that baled switchgrass would need to be grinded at the refinery so to improve its flowability through the refining process. We also assume that the refinery will have the same costs to accept grinded or pelletized feedstock.

Other assumptions made for transportation costs to the refinery are an average speed of 40 miles per hour at a cost of \$100 per hour for transportation via a contracted truck. We also limited the amount of feedstock by volume and placed maximum weight of 35 tons of feedstock in case of pellets since they have such a high density. This information was gathered from an interview with Mark Ruiter, a commercial agricultural transporter, who suggested a price between \$80 and \$100 per hour for the cost of a truck and driver.

**Table 4. Transport costs for each mode of preprocessing.**

	To Small Refinery			To Large Refinery		
	Baled	Ground	Pelletized	Baled	Ground	Pelletized
Transport Costs	\$0.17/gal	\$0.11/gal	\$0.05/gal	\$0.21/gal	\$0.13/gal	\$0.06/gal

As data in Table 4 above shows, the cost to transport the feedstock is directly correlated to the energy density of the switchgrass being transported. The least dense form of switchgrass is baled, followed by grinded, and lastly pelletized. For short distances, the cost of pelletizing does not outweigh the savings in transportation cost. At long distances pelletizing pays off because the energy density allows the truck to transport more mass per load.

#### **4.2.4 Refining and Destination Costs**

At this point, the feedstock must be converted into ethanol. This incurs a cost of \$2.20 per gallon (Weeks, 2008). Lastly, once the ethanol has been created, it must be shipped from where the refinery is to the petroleum refinery to be blended with normal gasoline. We assume the ethanol refinery is in the Midwest and the petroleum refinery would be on the East or West Coast. In this case, an estimate of 1,500 miles of travel from refinery to the blending station is reasonable. Transportation by rail costs are estimated using an equation given by Sokhansanj et

al. (2009). The equation given is:  $17.10 + 0.0277 * \text{Distance}$ . Distance is entered in kilometers, and the cost is given in \$ / Mg. Executing this equation and converting the costs to a per gallon basis, leaves an estimated cost to transport ethanol to the petroleum refinery of \$0.84 per gallon.

#### **4.2.5 Estimated Total Costs**

As shown below in Table 5, for the inputs mentioned, the price to transport grinded switchgrass to a small plant is the cheapest among the two chosen plant sizes and transportation forms of baling, ground, or pelleted switchgrass. There are several tradeoffs for transporting feedstock to a refinery. Baling the switchgrass at the farm is relatively easy and inexpensive to do, but it incurs additional handling costs which grinded and pelletized switchgrass do not have because they have bulk handling characteristics. Pelletizing allows the feedstock to be transported in a very dense form, reducing the number of trips required from farm to refinery, but there is additional cost in getting the feedstock in such a form. The total landed price is cheapest for ground feedstock to be taken to a small refinery because the feedstock doesn't have to travel as far from the farm to refinery. However, for the large refinery, the feedstock must come from a longer distance, and grinding and pelletizing are both similar in price.

Table 5. Estimate Landed Cost at the Refinery for Combinations of Harvesting Method and Refinery Scale.

		To Small Refinery (Capacity: 2000 Mg/day)			To Large Refinery (Capacity: 5000 Mg/day)			
		Baled	Ground	Pelletized	Baled	Ground	Pelletized	Combined
Supply Chain Stages	Details	Cost /Gallon	Cost /Gallon	Cost /Gallon	Cost /Gallon	Cost /Gallon	Cost /Gallon	Cost /Gallon
Planting & Cultivation	Current Technology	\$0.413	\$0.413	\$0.413	\$0.413	\$0.413	\$0.413	\$0.413
Harvest and Storage	Baling System	\$0.236			\$0.236			
	Loafing System		\$0.174	\$0.174		\$0.174	\$0.174	\$0.174
	Grinding at Farm		\$0.101			\$0.101		\$0.066
	Grinding at Plant	\$0.101			\$0.101			
	Pelletizing			\$0.179			\$0.179	\$0.061
Transport to Refinery		\$0.174	\$0.108	\$0.049	\$0.196	\$0.131	\$0.060	\$0.103
<b>Subtotal (from cropland to refinery)</b>		<b>\$0.924</b>	<b>\$0.796</b>	<b>\$0.816</b>	<b>\$0.946</b>	<b>\$0.819</b>	<b>\$0.827</b>	<b>\$0.817</b>

Because these values represent the average price for a gallon of ethanol, we also calculated where the cutoff distance makes it cheaper for a farmer to pelletize versus grind using the Excel solver function. Once the distance from farm to refinery is more than 22 miles, pelletized switchgrass will be cheaper to transport to a large refinery than ground switchgrass. This only affects the large refinery, so we also modeled a fourth, combined approach. Feedstock traveling less than 22 miles is grinded before transportation and feedstock traveling more than 22 miles is pelletized. This allows us to use each method for its strengths, the grinded feedstock for short hauls and pelletized feedstock for longer hauls. In this case, the estimated landed cost of feedstock to produce a gallon of ethanol is \$0.818. There are costs in the combined approach for



both pelleting and grinding, these were distributed, along with the transportation costs, proportionally to the amount of feedstock that was grinded versus pelleted. Compared with grinding, this saved only \$0.002 per gallon of ethanol. However, given that this large refinery processes 5,000 Mg of switchgrass a day and produces about 500,000 gallon a day, this saving is about \$810 per day. This means that the combined method can save about \$240,000 per year.

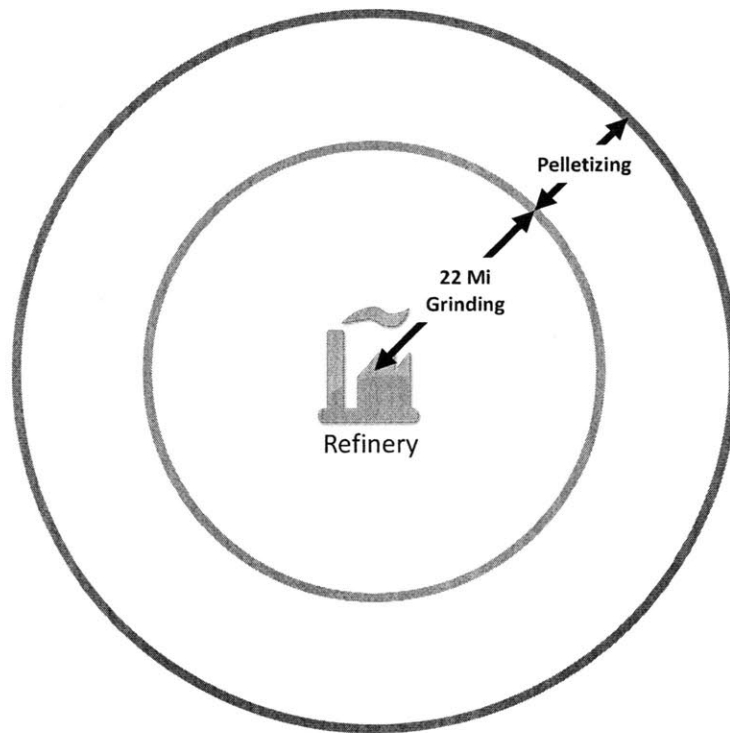


Figure 29. Schematic View of Combined Method.

As shown in Table 5, grinding is the most economic option for the small refinery, and the combined option is the most economic for the large refinery. We picked those two and added cost of ethanol conversion and transport costs to end consumer markets, as shown in Table 6. We did not find any evidence that economy of scale exists in ethanol conversion, so conversion cost is same for all the options. To calculate the transport cost, we assumed using a railroad trip of 1,500 miles from South Dakota to San Francisco or New York City.

**Table 6. Estimated total cost of a gallon of ethanol.**

	To Small Refinery / Grounded	To Large Refinery / Combined
<b>Subtotal (from cropland to refinery)</b>	<b>\$0.796</b>	<b>\$0.818</b>
Cost to Produce Cellulosic Ethanol (\$/gallon)	\$2.200	\$2.200
Cost to Transport Ethanol (1500 Miles, from South Dakota to SFC or NYC)	\$0.837	\$0.837
<b>Total Costs \$/ Gal</b>	<b>\$3.833</b>	<b>\$3.854</b>

In our analysis, the estimated costs are smaller for a smaller refinery because the feedstock does not need to travel as far.

## 5 Conclusion

For this paper, we analyzed various logistics issues such as location of cropland, harvesting and preprocessing. We chose switchgrass because this plant is a feedstock that shows great promise to be brought up to scale to support biofuel demand. Switchgrass grows well even in a marginal land, so switchgrass cultivation would not affect food production in the United States. Moreover, switchgrass is native species of the United States, so this plant has developed to be resistant to local diseases and require little care.

However, many challenges must be overcome before switchgrass farming can be brought up to scale. A problem in terms of cropland availability is the geographical dislocation of available land and land with higher switchgrass yield. Currently, yield of switchgrass is high in Corn Belt and Appalachian region, and croplands in these regions are not widely available for switchgrass production. We theorize a reasonable starting point for switchgrass production appears to be Kansas or northern Missouri, because there is enough cropland for switchgrass production and yields in these regions are higher than average.

To assess the cost efficiency of harvesting and preprocessing option, we set up six alternatives which are combinations of different harvesting, preprocessing, and refinery scale options. In our assessment, the most economic way to transport feedstock to a small refinery is the combination of loafing in the harvesting stage, and grinding in the preprocessing stage. The transportation to a large refinery is similar except we recommend farmers pelletize if the number of miles to the refinery is over 22.

Through our analysis, we have identified several supply chain issues, tradeoffs, and have suggestions for further research to be completed with respect to supply chain issues the biofuel market will face.

#### Supply Chain Issues:

- Currently biofuels are not cost competitive, they must rely on government subsidies to compete with petroleum based fuels
- Farmers are hesitant to grow a crop they have not grown before, such as switchgrass or canola, in case the market dries up unexpectedly, or in case government subsidies are not be renewed. Corn and soybean are known quantities with reasonably consistent demand.
- Upcoming shortage of commercial drivers may cause unpredictable increases biofuel feedstock transportation costs

#### Tradeoffs:

- Croplands in the locations with the highest yields are currently being used to grow food crops. The tradeoff is purchasing high yield cropland for a high price, or buying inexpensive land which cannot support high yields of biofuel feedstock.
- Transporting feedstock in its most energy dense form provides the lowest transportation costs. However, this requires additional costs and steps to preprocess the crop, such as pelletizing. Also, crops may be genetically engineered to start the chemical conversion of biomass to biofuel before arriving at the refinery.

- Increasing the use of food crops in biofuel production could raise food prices if the growth outpaces how much more of that crop is grown
- Increasing the size of the biofuel refinery also increases the costs to ship feedstock to the refinery

Our analysis showed a breakdown for how much on average a gallon of ethanol would cost to produce from switchgrass in 2010. Currently, ethanol production from switchgrass is not competitive without subsidies, but costs are coming down making it more competitive with petrochemical derived fuels.

#### Additional Research Opportunities:

- Examine the different ways to preprocess crops at the field going beyond our analysis of baling, grinding, and pelleting
- Perform a Carbon footprint analysis comparing biofuel production versus petrochemical fuel production

Our work has identified numerous supply chain issues and tradeoffs that will need to be resolved in the future if biofuels are to become competitive with petroleum based fuels. We look forward to further analysis which helps decrease the pricing gap between biofuels and petroleum based fuels.

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