Potential of Energy Production from Conserved Forages

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The world is at a critical time relative to energy supply. Fossil fuels have been the primary sources of energy in our lifetime and for more than 100 years before us. However, there are considerable concerns about how sustainable those sources will be for the future. One, we know that the supplies of crude oil, natural gas and coal are finite. These resources may not be exhausted in our lifetimes, but inexpensive crude oil is already coming to an end, raising the costs of food and other necessities of life in addition to the costs of the good and services that make life comfortable. Two, the demand for energy is going to continue to climb. The global human population is nearly 7 billion and expected to reach 9.5 billion by 2050 (U. S. Census Bureau, 2011). Beyond the increase in population is the reasonable desire by people in developing nations to live like people in developed countries where energy consumption per capita is much higher. Finally, use of fossil fuels is a major contributor to global warming as we return carbon that has been sequestered in the earth for millions of years back into the air as carbon dioxide. Logically, we need to seek solutions to our increasing demand for energy that minimize our carbon footprint.

Given these issues, plants, in general, including forages have a potential role in meeting that demand for energy because they fix carbon through photosynthesis, producing carbohydrates that can become an inexhaustible source of potential energy. Perennial forages are attractive for various reasons. One, both the monetary and energy cost of planting is spread over multiple years. Two, we already have the equipment for harvesting, storing and transporting this source of biomass. Three, legume forages or legume-grass mixtures need no or little nitrogen fertilizer, a major energy input for most crops. Four, forages can be grown on marginal agricultural lands and so do not compete with land that could be best utilized for direct human food production. Finally, perennial forages stabilize and enhance soil systems, minimizing erosion and building up soil organic matter, sequestering carbon.

In the United States, a major survey indicated that biomass from agricultural land and forestlands could sustainably supply more than one-third of the country's current petroleum demand (Perlack et al., 2005). To accomplish that, their assessment estimated that perennial forages would account for more than a quarter of the biomass, and crop residues, which could be harvested, stored and processed similarly to perennial forages, would represent one-third of the biomass. Consequently, there is a significant potential for forages and crop residues to contribute to the energy supply in the U.S. When one considers that the U.S. population has the highest per capita energy consumption, other countries may be able to produce an even larger fraction of their energy needs from forages.

The potential for forages to be sources of biomass for energy production in other countries will depend on many factors. A key will be the arable land base relative to the population and the amount of land needed for food production. Countries that are unable to meet the food demands of their human population are unlikely to have significant arable land resources that can be devoted biomass production. Countries that are net exporters of food are potentially good candidates for biomass production. However, even in countries with a surplus of food, the potential for energy production from biomass will depend upon the cost of producing energy from biomass compared with the cost of energy from more traditional sources, any incentives provided by governments for alternative energy sources, various political and social pressures to move toward alternative energy sources, and finally the infrastructure and technologies to accomplish efficient conversion of biomass to energy.

Our roles as scientists and engineers are to provide the information and technologies to permit biomass to be converted to energy. This includes increasing yields, efficiently harvesting crops, minimizing losses in storage, investigating potentials for pretreating crops in storage, developing systems for efficient transport to bioprocessing facilities, and discovering new technologies for the bioprocessing plant to improve the efficiency of energy production and maximize the value and utilization of the byproducts.

In this paper, I will briefly survey some of the opportunities for using forages as a source for energy. The most likely means of producing energy from forages are ethanol production (enzymatic breakdown of structural carbohydrates to simple sugars followed by fermentation of the sugars by yeasts or bacteria to ethanol), anaerobic digestion (fermentation of proteins, carbohydrates and lipids by various groups of bacteria to methane and carbon dioxide to methane) and combustion (generating electricity from turbines run by steam). Other possibilities will be discussed as well.

Species

A wide variety of forage species are being investigated as sources of biomass. In the U.S., C4 grasses have been the principal species studied because of their ability to produce high yields from one or possibly two cuttings per year. The emphasis has generally focused on grass species with modest fertilizer requirements. The most common species studied have been switchgrass (*Panicum virgatum*), various *Miscanthus* species, maize (*Zea mays*), forage sorghum (*Sorghum bicolor* subsp. *bicolor*) and sudan grass (*Sorghum bicolor* subsp. *drummondii*). The principal C3 grass investigated has been reed canarygrass (*Phalaris arundinacea*).

The C4 grasses are also the primary focus in other countries. Switchgrass and *Miscanthus* species are commonly being investigated for their potential. In Brazil, sugarcane (*Saccharum* spp.) is already a major source of sugar for ethanol production. It is a potential biomass source in the U.S. Elephant grass (*Pennisetum purpureum*) has been studied to a lesser extent.

Why have the legumes and C3 grasses been largely ignored? I think it is because the emphasis has been on obtaining low-cost, high-yield forage from one cutting per year. With many C3 grasses and legumes, multiple cuttings per year are necessary, and the total yields are lower than those of the C4 species that are being proposed which require only one cutting.

Another factor is nitrogen content. Nitrogen fertilizer is a major energy input to crop production. In fact, analyses of the net energy produced by ethanol production from maize grain sometimes show a negative balance, and fertilizer N is a major contributor to that (Farrell et al., 2006). Many of the C4 grasses being studied for biofuels have modest N fertilization requirements compared with other grass species. For example, optimum yields (~11 Mg/ha) in switchgrass were observed at fertilizer rates of 120 kg N/ha (Vogel et al., 2002). A rate of 100 kg N/ha did not improve the yield (28-38 Mg/ha, varying by year) of *Miscanthus giganteus* over that at 50 kg/ha (Danalatos et al., 2007). In addition, the nitrogen content of the C4 grasses is more than sufficient for the nitrogen needed by the yeast or bacteria used to produce ethanol. For example, the only additional nitrogen used in a proposed lignocellulosic ethanol production system from maize stover would be to grow the *Zymomonas mobilis* inoculum for the fermentation (Humbird et al., 2011). So excessive plant N is of little value for biofuel production. Legumes would have an advantage of requiring no N fertilization. However, the N contents of legumes are typically double or more than that of the grasses being proposed.

Is this focus on high yield, low N requirement grasses justified? Possibly. However, it is essential when selecting a prospective forage for biofuel production to find the lowest cost biomass that meets the requirements of the production system. Sugarcane is an ideal grass for ethanol production because of the high yield of biomass with high sugar content and low energy input. Under tropical conditions, energy in:energy out can reach 1:8 when used to produce ethanol (U. S. Department of Energy, 2011). Even under more temperate climates, energy in:out may be 1:3. With switchgrass or *Miscanthus* spp., we are looking at high yields, but these will only be economically feasible if the structural carbohydrates (cellulose and hemicellulose) can be enzymatically broken into sugars at reasonable cost. At our center, we have observed that switchgrass is much less amenable to enzymatic breakdown of structural carbohydrates than reed canarygrass (Digman et al., 2010). This suggests reed canarygrass might provide a higher yield of ethanol per hectare than switchgrass in some environments. So if our target is ethanol production, our focus needs to be the yield of readily available carbohydrates rather than total yield. If the target is methane production from anaerobic digestion of forages, methane yield may be more important than biomass yield. Similarly with pyrolysis, biodiesel, etc., yield of the target fuel per hectare is more important than yield of crop.

Another factor that affects the choice of forage is the value and utility of the byproducts of the process. In the U.S., maize grain is currently the main source of ethanol. However, the expansion of ethanol production from maize currently depends on selling the distiller’s grains as livestock feed, and this byproduct will inevitably displace other concentrates in livestock rations (Farrell et al., 2006). If forages will be grown for ethanol production for example, what will be the potential uses of the byproducts and will they provide significant revenue to make the whole process profitable?

A final issue relative to crop selection is how a forage fits into a crop rotation. Productivity of crops when continuously grown in the same field declines with time. Continuous cultivation of a crop may reduce soil fertility and increase disease and insect pressures. The inclusion of a legume forage like alfalfa (*Medicago sativa*) into a rotation provides substantial N credits to succeeding crops, greatly reducing fertilizer N needed for two or more years after the alfalfa is replaced.

Harvesting

It would appear that the technology for harvesting and handling forages is mature. Mowing equipment has been growing faster in capacity than the technology of cutting. Various means are used to speed drying: conditioning rolls on the mower, rakes, tedders, and mergers. Equipment for baling dry hay in various size packages has been available for decades: small rectangular bales, large rectangular bales, large round bales. Bales are readily transportable between farms today and can just as easily be transported between farms and a bioprocessing plant. Precision chop forage harvesters are the dominant means of chopping forages for ensiling and are growing in capacity as well. On large farms, chopping is often into trucks for rapid transport to the silo. Similarly trucks can readily move ensiled forage. Consequently the maturity of the harvesting and handling systems are an advantage forages have over crop residues such as maize stover as biomass feedstocks.

This maturity, however, does not mean that there is no need or opportunity for innovation in harvesting systems for forages being used as biomass feedstocks. Current harvesting machines are designed for traditional forage crops being cut at more immature stages relevant to meeting the nutritional needs of livestock. In contrast, forage for biomass is geared toward harvesting mature forage with thicker, more lignified stems that will be more abrasive and require more power to cut and process (U. S. Department of Energy, 2011). Mowing equipment may need to contend more frequently with lodged forage. Current harvesting equipment may be challenged to handle the high yields (>30 Mg/ha) of some of the *Miscanthus* species and may require specialized harvesting equipment. Creating stable, dry bales from some of the high yield species may be difficult.

Beyond improvements to current harvesting systems, there are opportunities for novel harvesting approaches. For example at the University of Wisconsin-Madison, a prototype forage harvester that strips leaves for direct ensiling and cuts stems to dry has been designed and tested (Shinners et al., 2007). The goal has been to create a high protein leaf fraction for use as an animal feed and a low protein fraction more suitable for biomass uses than the whole plant. It has been tested on switchgrass, reed canarygrass and alfalfa. Research on grasses has not shown as much potential in creating two divergent fractions as in alfalfa. Alfalfa stems wilt in several hours to typical ensiling conditions [35% dry matter (DM)], and the leaves when ensiled without wilting (~25% DM) have generally ensiled and preserved well (Muck et al., 2010). Consequently such a harvesting system appears to have potential in legumes for producing two crop streams, the leaf fraction for livestock and the stems for biofuels.

Storage/Pretreatment

There are two primary means by which forages can be stored – as dry hay or by ensiling. Dried forage has the advantage of being stable for long periods with low losses (<5%) if the forage is kept dry (e.g., Shinners et al., 2010). However if bales are stored outside without cover in humid climates, significant losses can occur and result in bales of variable quality. Biofuel production schemes benefit from consistent feedstock quality. So good storage environments for dry hay will most likely be required.

In humid environments, both tropical and temperate, production of dry hay may be difficult without rainfall damage during field drying. In these environments, ensiling of forages may be a better choice to reduce harvesting and storage losses. Normally we expect dry matter losses of 5 to 15% from ensiling. However, these losses are increased in a farm setting by the slow removal of silage from a silo, bag or pile, normally taking months to empty a silo while feeding livestock. Losses should be much lower when a silo is opened and rapidly emptied for transport to a biofuels facility. When bag silos have been emptied in a day, losses of 5% or less are possible (e.g., Shinners et al., 2010).

In the normal ensiling process, preservation is caused by a combination of the exclusion of oxygen and the natural fermentation of sugars by lactic acid bacteria to lactic acid and other products, lowering pH. The lack of oxygen prevents aerobic microorganisms from growing whereas the low pH is the principal mechanism inhibiting the growth of detrimental anaerobic microorganisms. These mechanisms will work whether the forage is destined for livestock or biomass uses.

When forage is to be a biomass feedstock, ensiling is an opportunity for pretreating the crop during storage, potentially increasing the availability of structural carbohydrates for ethanol or other biofuel production. Various typical standard silage additives have been tested on different forages and crop residues. Homofermentative lactic acid bacteria, the most common silage additives, can improve silage fermentation. However, these do not appear to substantially improve potential ethanol production (e.g., Table 1). A heterofermentative lactic acid bacteria like *Lactobacillus buchneri* may help aerobic stability of the ensiled forage by increasing acetic acid and decreasing yeasts and molds. This would be beneficial to minimize losses while the ensiled forage is transported from the farm to the biofuels production facility, but there could be negative consequences for ethanol production by yeast if acetic acid concentrations are high.

Table 1. Acid detergent lignin and cellulose concentrations (g/kg DM) and estimate of the sugar available for ethanol (SSC, relative fluorescence units/g DM) of ensiled maize stovers (Muck et al., 2008).

Treatment	Acid Detergent Lignin	Cellulose	SSC
Control	33	321	36000
Inoculant	34	322	37800
Enzyme	34	294	34200

Enzyme+Inoculant	36	291	38400
LSD at P<0.05	2.3	6.3	2380

Cell wall degrading enzymes were tried several decades ago for ensiling to increase sugar content from structural carbohydrates. These additives are not in most markets due to high cost relative to inoculants. However, they may have a role in partially degrading cell walls during storage. Several studies have looked at these (e.g., Table 1). Some of the current enzymes from major enzyme manufacturers reduce the amount of fiber in forages during silage storage, but the effect on potential ethanol production has been more modest. An alternate enzymatic approach may be to add enzyme-producing fungi to a moist crop, keeping the crop aerobic until enzyme activity is sufficient and then ensile the crop, allowing the enzymes to work during storage and killing the fungi by the anaerobic conditions (Tengerdy et al., 1996).

Less standard approaches have been investigated such as the addition of acids (e.g., H_2SO_4) and bases (NaOH, $Ca(OH)_2$), typically at a rate of 50 g/kg DM. Both acids and bases can be effective at breaking linkages in plant cell walls, particularly in the hemicellulose fraction. With these treatments, natural fermentation is inhibited by lowering or raising pH, respectively, out of the region of microbial activity so that there is good preservation of dry matter provided an anaerobic environment is maintained during the storage period. Both acids and bases have increased the ethanol potential of forages and crop residues (e.g., Table 2) and should reduce the degree of pretreatment needed at the biofuels plant. Research is still needed to determine optimum levels with various crops, develop safe methods for application at the farm level, and possibly develop techniques to recover product at the plant.

Table 2. Cellulose in grasses converted to ethanol by simultaneous saccharification/ fermentation after on-farm treatment of the grasses with sulfuric acid or calcium hydroxide at 50 g/kg DM and anaerobic storage (Digman et al., 2010).

	Cellulose Conversion (% of total)			
	Reed Canarygrass		Switchgrass	
Treatment	Acid	Lime	Acid	Lime
Treated	56*	20*	25*	27*
Untreated	21	17	13	14

* Treated is significantly different (P<0.05) from the untreated.

Transportation/Logistics

A major issue that is often ignored is that of moving biomass – from the field, to and from storage, to the processing plant and handling at the plant. After processing, products and byproducts are leaving the plant. The magnitude of the problem is illustrated in the analysis of Humbird et al. (2011), regarding the production of ethanol from maize stover. They analyzed the costs and design for a plant processing 2000 Mg dry stover/day and producing 330 L ethanol/Mg dry stover. This would require collecting approximately 10% of the stover in an 80-km radius. Twelve trucks per hour, 24 h/d, 6 d/wk, would be needed to supply the plant. The transportation in this example is somewhat magnified with maize stover because of its low density compared with most forages. Even so, the movement of forage biomass to a processing plant will be substantially more intense and more likely to have an effect on roads and infrastructure than the movement of hay from one farmer to another.

It is still to be determined what may be the most efficient way to move forage biomass from the field to the plant. Large rectangular bales of dry or wrapped moist forage would be easily transportable, but there are more limited options for pretreatment at the farm plus once the forage arrives at the plant considerable labor would be needed to break open bales and grind the forage. Chopped forage has the advantage of high harvest rates and ease of handling at the processing plant, but the lower density of chopped forage may increase transportation costs. An alternative to these standard options may be pelletization of forage at the farm (Sokhansanj et al., 2009). This would increase density of product shipped and would reduce grinding at the plant, but increase the cost of the feedstock at the plant gate. Beyond the form of the forage and its effects on transportation, there are various means of transport: truck, train, barge, etc. Lastly, the size of the plant may affect the most efficient solution. As plant size increases the area required to supply that plant increases and the average distance feedstock must transported increases. Greater distances may favor one means of handling and transport over another.

Ethanol

Ethanol is an attractive target for producing a liquid fuel from biomass. Ethanol can be substituted into gasoline (petrol) at low levels (e.g., 10% is common in the U.S.) for cars or trucks without any special provisions. Engines are available that run on ethanol or 85% ethanol/gasoline mixtures.

In the U.S., ethanol is largely produced from maize grain with amylases breaking down starch to glucose for fermentation by yeasts. In Brazil, sugarcane is the major source of ethanol. In both cases, ethanol production competes for these crops with other uses so that ethanol production costs can swing widely dependent on the demand in other food sectors.

In the longer term, ethanol production is expected to move to ligno-cellulosic sources such as forages. The steps to accomplish this will be different from those to produce ethanol from maize grain or sugarcane. Recently the National Renewable Energy Laboratory (Humbird et al., 2011) has published a report on their vision of a feasible (technically and economically) system for ethanol production from maize stover. One would expect a similar process for other forages. The steps are as follows:

- Milling of feedstock to a mean size of 4-6 mm.
- Pretreatment with dilute sulfuric acid at high temperature and pressure for a short time (18 mg sulfuric acid/g dry matter (DM), 158°C, 5.5 atm, 5 min).
- Simultaneous enzymatic hydrolysis of structural carbohydrates and fermentation of sugars, using enzymes prepared at the plant and *Zymomonas mobilis* to ferment both 5- and 6-carbon sugars to ethanol.
- Enzyme mixture prepared by growing a fungus (like *Trichoderma reesei*) aerobically on glucose.
- The fermentation mixture would be distilled to collect the ethanol and the remaining mixture would be separated into liquid and solid fractions.
- The liquid would go through anaerobic and aerobic digestion to produce methane and be cleaned sufficiently so that the water could be recycled.
- Solids would be dried and used for combustion to produce high-pressure steam for electricity production and process heat for pretreatment and distillation.

By their analyses and assumptions, ethanol could be produced for a minimum selling price of $0.57 per liter assuming they could purchase feedstock at $64.50/Mg DM. This selling price estimate is substantially lower than similar estimates less than 5 years ago ($0.93/liter), but still higher than market surveys for the cost of producing ethanol from maize grain and sugarcane, $0.40 and $0.30/liter, respectively. With continued advancement of technologies, I think it is reasonable to assume that the costs of producing ethanol from forages will come down and become economically viable. There is still research to be done to develop low cost systems to produce ethanol, both issues at the farm and plant. Certainly other mechanisms for pretreating and fermenting forages are under investigation.

A concern is that only 30% of the carbon that enters the ethanol plant will leave in ethanol. Most of the rest leaves as carbon dioxide. Energy recovery is much greater, with 72% of the carbohydrate energy from the crop being captured as ethanol (Humbird et al., 2011). However, petroleum inputs for producing ethanol from switchgrass (0.1 MJ petroleum/MJ ethanol) were calculated to be similar for the best scenarios for maize, and net greenhouse gas production (12 g CO_2/MJ ethanol) for producing ethanol from switchgrass was approximately 20% of that for maize (Farrell et al., 2006). In addition the net energy of producing ethanol from switchgrass (23 MJ/L) was found to be more than twice that of the best analysis for producing ethanol from maize (9 MJ/L).

Anaerobic digestion

Particularly in Europe there has been a growing interest in fermenting silages in anaerobic digesters to produce methane. Anaerobic digestion has been used for decades in treating waste streams (e.g., sewage sludges and manures), producing methane. The methane has been used for heating or electric generation. In some cases, it has just been flared where waste treatment was the main goal and there was no immediate use for the methane.

Methane production is a multistep process carried out by a variety of anaerobic bacteria. Sometimes it is described more simply as a two-step process whereby various bacteria breakdown and ferment proteins, carbohydrates and lipids to acetic acid, hydrogen, carbon dioxide, ammonia, and hydrogen sulfide. Then methanogens convert the acetic acid, hydrogen and carbon dioxide to methane. The gas produced by the digester will be a mix of methane, carbon dioxide and traces of other gases, typically 50 to 70% methane. Typically in an industrial process the process is carried out in a single, stirred tank with retention times of 20 to 30 days. Farm-scale digesters may be plug-flow covered trenches with manure entering on one end and the digested waste leaving on the other end.

With anaerobic digestion of forages and other crops, cattle or other livestock are being bypassed. In a basic scheme, forages would be harvested and ensiled to preserve the crop until digested. The silages would be added to the digester on a daily basis, possibly with water, other organic products or wastes. The waste exiting the digester would be stored and spread back to cropland. The methane produced by the digester could be used for heating, electric generation, or cleaned of carbon dioxide and compressed for addition to natural gas pipelines.

The energy return from methane production could be substantial. (Berglund and Borjesson, 2006) calculated energy balances for methane production from various sources.

With forages, energy inputs would be 40% of energy output or the energy from methane is approximately 2.5 times greater than the energy invested in the process.

Methane yields of up to 0.50 m^3/kg volatile solids (VS) have been reported. Assuming a more modest yield of 0.30 m^3/kg VS and a crop yield of 10 Mg/ha with an ash content of 50 g/kg DM, methane production would be 2850 m^3/ha or approximately 101 GJ/ha.

While anaerobic digestion is a relatively mature technology in waste management, considerable research is needed to optimize this technology for ensiled forages. Research is in the relatively early stages to investigate silage additives and ensiling conditions on methane potential as well as pretreatments such as NaOH to increase methane yield (e.g., (Pakarinen et al., 2009). There are also variations being investigated such as also producing hydrogen (Pakarinen et al., 2009) or using liquid-solid separation, digesting only the liquid fractions and using the solids for combustion (Buhle et al., 2010; Richter et al., 2011a, b).

Combustion

Combustion has already been mentioned in relation to ethanol and methane production for utilization of byproducts. Dry forages could be substituted for coal or co-fired with coal for electric generation. In various places, co-firing has been tested at pilot and full-scale. The lower energy density, variability in energy content and the higher ash content of forages compared with coal suggest that such enterprises will be limited. However, there are plants generating electricity from combustion of various biomass sources, largely wastes from the paper, lumber and sugarcane industries (Farrell and Gopal, 2008).

Recently, a life-cycle assessment was made for various renewable energy sources for transportation (Campbell et al., 2009). Ethanol and combustion for electricity produced from either maize or switchgrass were compared. Switchgrass produced more net mileage and more greenhouse gas offsets than corn. Further, the analysis showed that electricity production from switchgrass on average resulted in 81% more net mileage and 108% more net greenhouse gas offsets than if the switchgrass was converted to ethanol.

This analysis suggests that combustion to produce electricity may be a promising route for producing energy from forages, but there are challenges. Efficiencies for the conversion of biomass to electricity are currently in the range of 20 to 25% (Farrell and Gopal, 2008). To improve those efficiencies, research is needed in regard to handling and preprocessing the biomass as well as in reactor design. Also strategies are needed to deal with the variability in the biomass feedstock and its effect on generating plant performance.

Other Possibilities

Other technologies for converting forages to fuel or electricity are not as advanced as ethanol or methane. Pyrolysis, the heating of organic substances under pressure in anaerobic conditions, is capable of producing various biogases, bio-oils and chars. The products vary by crop and treatment conditions. Forages are being studied [e.g., switchgrass (He et al., 2009); elephant grass (Strezov et al., 2008)]. However, considerable research is still needed to find which products are the best targets of pyrolysis of forages and the optimum conditions for making those products. Only then will it be possible really analyze if the process could be economically viable.

Fermentation of forages by *Clostridium acetobutylicum* to n-butanol is now receiving attention (e.g., Pfromm et al., 2010). Butanol could be converted to gasoline, making it more attractive than ethanol. However, the energy yield of butanol from corn or switchgrass is approximately half that of ethanol. This makes butanol production from forages an unlikely target biofuel in the near term without major advances.

Sustainability

Today it appears that we are on the doorstep of seeing forages utilized for energy production – ethanol, methane, electricity. Assuming we solve the technical challenges, there are still issues to having a stable, sustainable and profitable energy production enterprise from forages. First, we need to have a forage production system for biofuels that is not in competition with food production. In the U.S., we have seen maize prices climb dramatically with the added demand for maize to produce ethanol. This is not in the best interest of average citizens as they see more of their income spent on food. As maize prices increase, the economic viability of ethanol production from maize declines. Forages do have an advantage over grains because they can be grown on marginal soils that are unsuitable for other crops. This could potentially minimize competition if we bring marginal lands into forage production.

Second, forage production should be tied to a good crop rotation scheme. Crop rotations have long been recognized for maintaining soil fertility, increasing yields, and minimizing plant diseases and insect pressures. For each environment, we need to study what mix of crops holds the best potential. We may have a situation where multiple energy crops could be grown in rotation, including grasses, legumes and grains.

Third, even if we can technically produce biofuels from forages, we need the infrastructure to make the production system work. Farmers need to be paid a fair value for their crops for them to have an incentive to raise those crops. Roads and transportation systems need to be in place to accommodate the movement of forages to the plant and biofuels and byproducts from the plant.

Finally, we need to look at potential byproducts of biofuel production for both economic and environmental reasons. Currently in the U.S., distiller's grains are a significant income stream in ethanol production from maize, keeping a valuable feed from merely being disposed in landfills or spread on fields. Schemes to separate leaves and stems or liquid and solid fractions of forages may maximize the economic value of both fractions. We need to look at novel products that could be derived from those fractions beyond biofuels. For example, several groups are investigating lactic acid production from various forage fractions. Perhaps there are high value proteins or other compounds that could be derived from forages in addition to energy that would support the profitability of the whole enterprise.

We live at an exciting time when we have the possibility of generating all of our energy needs from renewable sources. Forages will most certainly play a role in that, and we have the challenge to help make that happen.

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