2014

# Future Prospects for Corn as a Biofuel Crop

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**Abstract**

Ethanol production from corn grain has increased signifi cantly during the past ten years in the US. This increase was driven by government policy guided by the Renewable Fuel Standard (RFS) and embodied in the Volumetric Ethanol Excise Tax Credit and other legislation created to promote a biofuels industry. As corn grain ethanol production approaches the target set out in the RFS, the industry is looking to develop capacity for producing advanced biofuels, primarily from agricultural wastes and dedicated energy crops. The residues remaining following corn harvest have been identifi ed as a voluminous and readily available feedstock for advanced biofuels. However, these residues provide important ecosystem services and their complete removal may exacerbate environmental problems associated with soil erosion, water quality, nutrient cycling, and carbon sequestration. Alternative crop management practices need to be developed and implemented to ensure that these services are maintained or enhanced for biofuel production from corn residues to be sustainable. Management practices such as reduced tillage, use of cover crops, site-specifi c harvest intensities, and shifting marginal land currently used for corn production to perennial energy crops show potential for allowing removal of corn residue while maintaining ecosystem services.

**Keywords**

ethanol, soil erosion, soil quality, water quality, carbon seqestration

**Disciplines**

Agronomy and Crop Sciences | Environmental Sciences | Oil, Gas, and Energy

**Comments**

This is a chapter from Moore, Kenneth J., Douglas L. Karlen, and Kendall R. Lamkey. 2014. Future prospects for corn as a biofuel crop. pp. 331-352. In: Stephen L. Goldman and Chittaranjan Kole (editors) Compendium of Bioenergy Plants: Corn, Science Publishers, Taylor & Francis Group, LLC. Posted with permission.

CHAPTER 13

# Future Prospects for Corn as a Biofuel Crop

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**ABSTRACT**

Ethanol production from corn grain has increased significantly during the past ten years in the US. This increase was driven by government policy guided by the Renewable Fuel Standard (RFS) and embodied in the Volumetric Ethanol Excise Tax Credit and other legislation created to promote a biofuels industry. As corn grain ethanol production approaches the target set out in the RFS, the industry is looking to develop capacity for producing advanced biofuels, primarily from agricultural wastes and dedicated energy crops. The residues remaining following corn harvest have been identified as a voluminous and readily available feedstock for advanced biofuels. However, these residues provide important ecosystem services and their complete removal may exacerbate environmental problems associated with soil erosion, water quality, nutrient cycling, and carbon sequestration. Alternative crop management practices need to be developed and implemented to ensure that these services are maintained or enhanced for biofuel production from corn residues to be sustainable. Management practices such as reduced tillage, use of cover crops, site-specific harvest intensities, and

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shifting marginal land currently used for corn production to perennial energy crops show potential for allowing removal of corn residue while maintaining ecosystem services.

**Keywords:** ethanol, soil erosion, soil quality, water quality, carbon sequestration

## Current Status—A Grain Dominated System

Few people would have predicted the rapid increase in ethanol production from corn grain that occurred during the last decade. This increase was driven primarily by a "blender's credit" that subsidized the blending of ethanol with gasoline (Hoekman 2009). The credit, which helped ensure a market for corn ethanol, assured a reasonable return to capital investment and enabled the industry to respond by expanding rapidly. For both farmers and their neighbors, investment in ethanol plants created greater local demand and higher prices for corn grain while also providing an increased number of well-paying employment opportunities that helped reinvigorate the economies in many small rural communities (NAS 2009). Some argue that the number of jobs added to the local economy has been overestimated, and when the increasing corn demand for ethanol production was coupled with that for animal feed to meet increasing demands from Asia, land values and input costs have also increased (Low and Isserman 2009).

In 2006, ethanol produced from corn exceeded that produced from sugarcane worldwide (Balat and Balat 2009) and ethanol production from corn has continued to expand exponentially (Fig. 1). There were 204 plants in the US in 2011 producing 13.5 billions of gallons of ethanol (Renewable Fuels Association 2012) and the US actually exported close to a billion gallons to Brazil making the US the leading exporter of ethanol in the world (USDA 2011). The rapid rise in US grain ethanol production is an astounding accomplishment, and as we look forward to further increases in the production of it and other biofuels from sources other than corn grain, it is worthwhile to consider the factors that made corn ethanol production so successful.

Several factors have contributed to the success of the corn ethanol industry. The blender's credit, officially known as the Volumetric Ethanol Excise Tax Credit, was authorized in 2004 as part of the Jobs Creation Act (H.R. 4520). It provided manufacturers of liquid fuels with an economic incentive to blend ethanol with petroleum products. The original tax credit was 51 cents per gallon on a pure ethanol basis, but it was reduced to 45 cents per gallon in 2009 and then phased out entirely at the end of 2011. A tariff on ethanol imports was also imposed to discourage blenders from

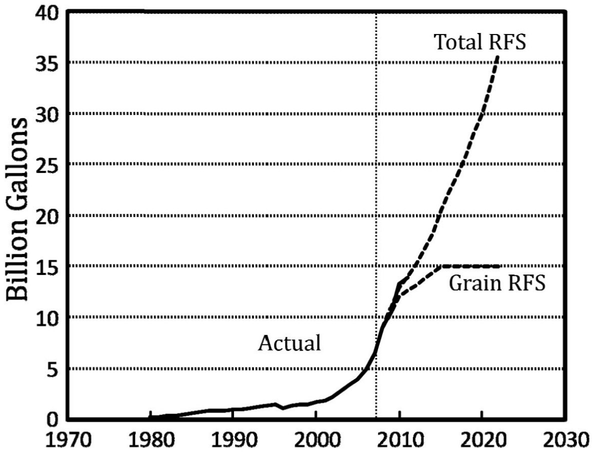


**Figure 1** US ethanol production (1980–2011) and production Renewable Fuel Standard targets (2008–22). Data source, Renewable Fuels Association 2012.

using foreign sources of ethanol (Elobeid and Tokgoz 2008). This latter measure was introduced largely to discourage importation from Brazil, which had levied a protective tariff on ethanol imports. The US government also provided tax incentives to encourage investment in the development of ethanol production plants. A tax credit of ten cents per gallon was given to plants producing less than 60 million gallons per year. This contributed significantly to the proliferation of ethanol plants throughout the US Corn Belt, but some argue that such incentives and tax credits are not wise because of their impact on our national debt. However, as pointed out by Rossali-Calli (2010) the $7.7 to 11.6 billion given to the ethanol industry from 1979 to 2000 was really miniscule when compared to the $135 to 150 billion in tax breaks given to support the fossil fuel industries.

Coupled with these incentives were mandates requiring fuel manufacturers to produce increasing levels of biofuels beginning in 2006 (Hoekman 2009). The original Renewable Fuel Standard (RFS) was implemented in the Energy Policy Act of 2005 (P.L. 110-58) and was amended in the Energy Independence and Security Act of 2007 (P.L. 110-140). These acts set targets for the production of biofuels and are overseen by the EPA (De Gorter and Just 2009). The schedule set by the RFS increases the mandate from 9 billion gallons of renewable fuels in 2008 to 36 billion gallons in 2022 (Fig. 1). Ethanol produced from corn grain is capped at 15 billion gallons in 2015. The remaining 21 billion gallons are to be produced from feedstocks other than corn grain. Corn residue, the nongrain portion of the crop, is likely to contribute significantly to the production of these second generation biofuels. How much corn residue will contribute to meeting the RFS from here forward remains to be seen, but several studies evaluating the feasibility of producing fuel from biomass recognize it as a major feedstock (Perlack et al. 2005).

Another factor that contributed initially to the increase in ethanol production was the low price of corn. From 1973 through 2005, US corn grain prices averaged $2.36 ± 0.40 bu$^{-1}$ of grain (25 kg), but for 2006 through 2010 prices averaged $3.94 ± 0.59 bu$^{-1}$, before spiking in 2011 to $6.01 (NASS 2011). Prior to the development of an ethanol market for corn grain, surplus production, often encouraged by federal subsidies, kept corn prices relatively low, but as the growing ethanol industry increased demand for corn grain, the price farmers received increased. Part of the rationale for pursuing an aggressive agenda in developing a corn ethanol industry was to create demand for corn that would result in increased prices and ultimately returns to farmers. More recently, the increased global demand for corn grain and the corresponding increase in its value has raised the cost of ethanol production resulting in narrower margins but also forcing increased efficiency (Babcock 2008). A recent processing change has been the increased oil extraction from the distiller's solids, but from the perspective of animal producers using DDGs for feed, this change has not been desirable.

Rural communities have benefited from construction and operation of corn ethanol production facilities (Low 2009). The industry has created new jobs in rural areas and provided local investment and marketing opportunities for corn grain. Looking forward to further expansion of ethanol produced from second-generation biomass, Ugarte et al. (2007) predicted substantial job creation in the agriculture and energy sectors. They further predicted that due to the broad geographic distribution of biomass production that many regions of the country will benefit.

As corn grain ethanol production approaches the target set out in the RFS, it is important to consider why production targets are shifting to more advanced biofuels. First, there was the realization that there is an upper limit in the amount of ethanol that can be produced from corn grain without negatively impacting food markets. Today, nearly 40% of the US corn crop is used to produce ethanol (NASS 2011), with most of the remainder being used in livestock feed. Only a small percentage contributes directly as an ingredient to foods produced for human consumption. Another factor favoring advanced biofuels is the recognition that the capacity to produce corn is constrained by land resources and even if the entire US corn crop were processed into ethanol it would only account for 12 to 15% of annual US gasoline consumption (Perlack et al. 2005).

In the intervening period since the original RFS targets were set, the specter of indirect land use change emerged and changed many perceptions regarding the sustainability of using corn grain to produce fuel (Searchinger et al. 2008). The concept behind indirect land use change is that shifting land use in the US to produce biofuels will cause a proportional conversion of land in other parts of the world to food production. Indirect land use change assumes that markets will respond in ways that result in deforestation and other practices that will have a negative impact on global carbon balance. While the theory is based on assumptions that may or may not be valid, it has nevertheless had a sobering effect on development of biofuels policies and has been a consideration in the development of revised RFS targets (EPA 2009). Furthermore, while production of biofuels on land already in cultivation could lead to a net decrease in greenhouse emissions relative to fossil fuels, tilling previously uncultivated land elsewhere could lead to increased global greenhouse gas (GHG) emissions. This could mean that instead of having a positive effect on climate change factors, using land that was previously used for food production for fuel crops could actually exacerbate the problem.

Despite all of the tangible positive benefits that have accrued from corn ethanol production concerns have been expressed about the industry and the impacts it could have on the environment and global food security (Farrell et al. 2006). Implicit in these discussions is recognition that corn ethanol production represents only a small improvement over petroleum products in terms of conversion efficiency. The energy derived from a unit of corn ethanol is on the scale of 1.4 times of that used to produce it (US DOE 2006). While it has become apparent that the efficiency of the grain to ethanol conversion can be improved, it is clear that much greater efficiencies will be realized from second-generation fuels (Hettinga 2008; Liska et al. 2009). The fossil fuel efficiency ratio for ethanol produced from biomass is predicted to be greater than 10, almost an order of magnitude over that which can be obtained in the conversion of grain to ethanol (US DOE 2006). There have also been several questions raised regarding the balance between food and fuel. Unfortunately, the issue has been portrayed very simplistically by the popular press generally neglecting the complex interactions with factors such as climate change, livelihoods, development goals, and misconceptions and misunderstandings among academics, policy makers and the public (Rosillo-Calle and Johnson 2010). Both the benefits and risks of biofuels are very context specific—a system that is sustainable in one location may not even work in another. For example potential impacts of climate change on biofuel feedstock production could be any one of several limiting factors including (1) lack of water, (2) soil erosion, (3) salinity, or (4) lack of investment (Rosillo-Calle and Johnson 2008; Wilhelm et al. 2011).

The RFS is designed to encourage a shift to second-generation biofuels in 2015. After this time, further expansion of the industry will be based on biofuels derived from agricultural and forest residues as well as energy crops. As the incentives shift to producing and using advanced biofuels, corn crop residues will play an increasingly important role in biofuel production. The Billion Ton Update (BT2), a study published by the US DOE (2011) to assess and predict potential biomass feedstock resources in the US, estimates that corn stover could account for between 65 and 140 million tons or as much as 10% of available feedstock for biofuel production in 2030. The concentration of corn production in the Midwest US and relative availability of corn residues in the region have led many analysts to predict that an industry based on cellulosic fuels will take root there and spread to other areas as technologies develop and other herbaceous and woody energy feedstocks are established.

There are obvious advantages for using corn residue as a biofuel feedstock. The practice will allow coproduction of food and fuel on the same land and therefore will not necessarily result in significant land use change. Corn residues currently represent the largest readily available supply of feedstock (DOE 2011). US production of corn grain exceeded 12.5 billion bushels in 2011 (NASS 2012), which means that by assuming a harvest index of 0.5, more than 290 million tons of residue will be produced. For several reasons, a substantial amount of this material will not be available to produce biofuels, but its sheer abundance underscores the potential. After evaluating ethanol production from corn grain and stover with respect to energy use, energy security, and resource conservation metrics, Lavigne and Powers (2007) concluded that using corn stover as a feedstock was more consistent with US national energy policy priorities than producing ethanol from grain.

Other advantages for embracing the use of corn residues for bioenergy production relate to the well-developed nature of the crop and the industry that supports it. Much of the infrastructure for producing, harvesting and transporting corn residues already exists. In terms of genetics, the corn industry has excelled at discovering fundamental knowledge about the species and translating that information into superior crop performance. The underlying knowledge for developing hybrids for coproduction of energy and grain as well as the research infrastructure for its expansion already exist. The Corn Belt has an extensive transportation infrastructure for moving agricultural products from the field, to storage, processing facilities and export markets outside the region. Time will tell, but collectively these reasons suggest that the nascent cellulosic fuel industry will likely develop around corn biomass feedstock in the US Midwest and migrate to other areas with different feedstock materials.

## Concerns Regarding the Use of Corn Stover as a Biofuel Feedstock

As previously discussed, corn stover, the aboveground material left in fields after corn grain harvest, was identified by Perlack et al. (2005) as a primary biomass source in the Billion Ton Study (BTS). However, this raised concern among many soil scientists because harvesting crop residues for biofuel feedstock or any other purpose will decrease annual carbon input and may gradually diminish soil organic carbon (SOC) to a level that threatens the soil's production capacity (Johnson 2006). Concerns were accentuated knowing that for many soils artificial drainage, intensive annual tillage, and less diverse plant communities have already reduced SOC by 30 to 50% when compared to precultivation levels (Schlesinger 1985). Returning a portion of crop residues to replenish SOC was deemed essential for sustainability (Lal 2004a,b; Wilhelm et al. 2007).

With regard to advanced biofuels, cellulosic biomass has numerous advantages over corn, soybean, or other grains, including its availability from sources that do not compete with food and feed production. Biomass can be reclaimed from municipal solid waste streams and from residual products of certain forestry and farming operations (Brick 2011). It can also be grown on idle or abandoned cropland thus minimizing competition with food, feed and fiber production. Plant biomass has the potential to play an important role in the global energy future because it can be grown in a sustainable manner and converted into liquid transportation fuels using either biochemical or thermochemical conversion processes. Biofuels made from renewable feedstocks are an attractive alternative to gasoline because they can decrease the net release of greenhouse gases (GHG) from the transportation sector (Karlen et al. 2011).

Using the lessons learned from grain ethanol production, it is important to recognize that while there is sufficient rationale and scope for including corn residues as an advanced biofuel feedstock, the advantages must be balanced against potential environmental concerns. Currently, most corn residues are left in the field after harvest because they have significant impact on the cropping system. They are involved in nutrient cycling, water balance, carbon sequestration and very importantly for helping to prevent soil erosion caused by wind and water (Johnson et al. 2009, 2011). These are important ecosystem functions and harvesting corn residues will affect the performance of each (Johnson et al. 2007). Simply removing the residues without an attempt to replace the ecosystem services they provide is not an option on many sites (Johnson et al. 2010).

Harvesting corn stover as a feedstock for biofuel production could have many benefits, if the process is developed as a complete system that considers all ecosystem services provided by crop residues (Larson 1979; Karlen et al. 1984; Wilhelm et al. 2010). This includes conserving soil water, reducing surface runoff and evaporation, increasing infiltration rates, controlling soil erosion, recycling plant nutrients, providing habitat and energy for earthworms and other soil macro- and micro-organisms, improving water quality by denaturing and filtering of pollutants, improving soil structure, preserving native habitats, and maintaining biodiversity. Crop residues can also help reduce nonpoint source pollution, decrease sedimentation, minimize risks of anoxia and dead zones in coastal ecosystems, increase agronomic productivity, advance food security, and mitigate flooding by holding water on the land rather than allowing it to run off into streams and rivers (Kimble et al. 2007).

## *Long-term Productivity Effects*

It is well recognized that excessive crop residue harvest will have negative consequences on long-term soil productivity, especially if conventional, relatively intensive (i.e., moldboard plowing, chisel plowing, multiple diskings, etc.) tillage practices are used (Larson 1979; Wilhelm et al. 2004; Blanco-Canqui and Lal 2007). However, by adopting practices such as strip-tillage, or no-tillage it may be possible to harvest a portion of the crop residues without impairing long-term soil productivity. This is especially true where improved hybrids and management are consistently resulting in grain yields exceeding 200 bu $ac^{-1}$ and producers are actually facing "crop residue management" problems due to subsequent N immobilization or poor stand establishment due to inadequate soil-seed contact. Those latter conditions are the primary assumptions for estimates of available corn stover in the revised Billion Ton Study (BT2) (DOE 2011).

Representative corn grain yields from several ongoing field studies listed above are summarized in Table 1. Overall, they show that harvesting a portion of the corn stover for several years did not have a negative impact on subsequent grain yields. The negative response for the MN-NT95 site was caused in part by a K deficiency that developed due to long-term no-tillage (since 1995). Also, the lower yields for several of the nonremoval Iowa sites were caused by N immobilization and early-season plant N deficiencies. Exact stover harvest rates varied among locations but generally averaged 1 to 1.5 t $ac^{-1}$ for the moderate removal rate and 2 to 2.5 t $ac^{-1}$ for the high-removal rate.

**Table 1** Representative long-term corn grain yield (bu/acre) in response to stover harvest on ARS-Renewable Energy Assessment Project (REAP) and Sun Grant Regional Partnership (RP) research sites.

| Location | Tilage | Site-Years | Removal Rate | | |
|---|---|---|---|---|---|
| | | | None | Moderate | High |
| MN-NT95 | No-tillage | 7 | 130 | 134 | 122 |
| MN-NT05 | No-tillage | 6 | 152 | 155 | 150 |
| MN-CP | Chisel plow | 7 | 156 | 162 | 164 |
| PA1 | No-tillage | 4 | 147 | 153 | 145 |
| IL-NT | No-tillage | 19 | 179 | 194 | 197 |
| IL-CP | Chisel plow | 19 | 205 | 199 | 202 |
| SD1 | No-tillage | 4 | 118 | 120 | ND† |
| IA-Conv | No-tillage | 4 | 168 | 179 | 189 |
| IA-Conv | Chisel plow | 4 | 171 | 188 | 188 |
| IA-High Pop | No-tillage | 4 | 168 | 188 | 183 |
| IA-High Pop | Chisel plow | 4 | 173 | 189 | 188 |
| IA-Biochar 1 | Chisel plow | 4 | 168 | 190 | 193 |
| IA-Biochar 2 | Chisel plow | 4 | 177 | 185 | 191 |
| **Average** | **----** | **7** | **162** | **172** | **176** |

†ND – Not determined

## *Soil Quality Effects*

Six of the most critical environmental factors that limit sustainable agricultural residue removal are: soil organic carbon, wind and water erosion, plant nutrient balances, soil water and temperature dynamics, soil compaction, and offsite environmental impacts (Wilhelm et al. 2010). One method for evaluating the impact of harvesting corn stover and other feedstock materials is to use soil quality assessment. During the past 20 years, several studies (Karlen et al. 1997, 2006; Liebig et al. 2006; Wienhold et al. 2006; Zobeck et al. 2008; Jokela et al. 2009) have used the Soil Management Assessment Framework (SMAF) developed by Andrews et al. (2004) to monitor and evaluate soil biological, chemical, and physical responses to various land uses, farming systems, and management practices. We expect that the potential land-use changes associated with development of a sustainable biofuel industry will present another opportunity to use the SMAF to guide and quantify long-term effects of such endeavors.

By focusing on soil quality impacts, the perception that crop residues are not important for modern grain production systems will hopefully be dispelled. Crop residues, both above and belowground, protect land from the ravages of wind and water erosion (Soil Conservation Society of America 1979). They also supply an annual input of carbon and replenish several of the essential plant nutrients that are assimilated during crop production

(Wilhelm et al. 2004). Traditionally, a limited amount of corn stover has been harvested for animal feed and bedding. This is usually done in a localized manner, with a substantial portion of the residues being returned to the soil, often mixed with animal manure and thus not only adding carbon but also recycling other nutrients to soils in the same location, or at least on the same farm, from whence they came.

Despite the recycling that can occur when crop residues are utilized as animal feed and then partially recycled through the manure, long-term research has conclusively shown that crop production practices often result in TOC loss (Paustian et al. 1997). Losses are often greatest where corn is produced on soils having artificial drainage, intensive annual tillage, and less diverse plant communities. Collectively, these factors have been shown to have reduced TOC by 30 to 50% when compared to precultivation levels (Schlesinger 1985). Such TOC loss can have many detrimental effects on soil productivity (Gollany et al. 1991; Mann et al. 2002) and quality (Liebig et al. 2005; Moebius-Clune et al. 2008). However, soil and crop management practices that decrease tillage and crop residue incorporation can reduce TOC losses and may even increase TOC to a limited extent (Burke et al. 1989).

Previous long-term studies, such as those by reviewed by Paustian et al. (1997), showed the importance of preventing excessive stover harvest, which was recognized in the BTS. As a result, the BTS authors limited their estimates of available feedstock in order to protect soil resources from wind and water erosion (Nelson 2002; Graham et al. 2007), but they did not account for the amount of stover required to sustain TOC levels. Soil carbon assessments are a key component of the several studies.

## *Soil Erosion Effects*

In 1979, Larson conducted one of the first large-scale studies focused on crop residue removal and its effect on soil erosion using the Universal Soil Loss Equation. This study included the Corn Belt, the Great Plains, and the Southeast. The effect of tillage practices, i.e., conventional, conservation, and no-till and residue management were investigated with respect to rainfall and wind erosion, runoff, and potential nutrient removal. This study found that for the management practices and crop yields at the time, nearly 49 million metric tons of residue was available annually throughout the Corn Belt. Soil carbon, tilth, and productivity maintenance were not considered. As a result of limited interest in agricultural residues for energy production during the 1980s and 1990s, no additional large spatial scale assessments of residue availability were performed until more than two decades after Larsen's study. Nelson (2002) used the Revised Universal Soil Loss Equation

(RUSLE) and Wind Erosion eQuation (WEQ) to expand on Larson's analysis to develop a methodology to estimate the sustainable removal rates of corn stover and wheat straw at the soil-type level. This methodology considered rainfall and wind-induced soil erosion as a function of reduced and no-till field management practices. In 2004, Nelson et al. used the same approach to assess five other major one- and two-year cropping rotations, e.g., corn-soybean. Neither of these studies addressed soil organic matter as a function of removal. Researchers have also used the Revised Universal Soil Loss Equation, Version 2 (RUSLE2) and/or Wind Erosion Prediction System (WEPS) to address a number of erosion-based questions on crop residue removal.

Crop residue reduces water erosion primarily by dissipating rainfall energy and slowing overland flow of water so that it can infiltrate and be retained in the soil. It helps mitigate wind erosion by slowing wind speed at the soil surface—air interface and reducing opportunities for soil movement through suspension, saltation, or surface creep (Fig. 2). For controlling wind erosion it is not only important to retain an adequate amount of surface residue cover, but also to have significant vertical orientation.

In addition to the physical loss of soil particles and the nutrients or other materials attached to them through either water or wind erosion, crop residues are also important for helping to form and stabilize soil aggregates. Data from the Brookings, South Dakota show the impact of what would be considered excessive crop residue harvest based on the long-term average grain yields (Table 2). The long-term effect of excessive corn residue harvest is that the fraction of small aggregates and thus the

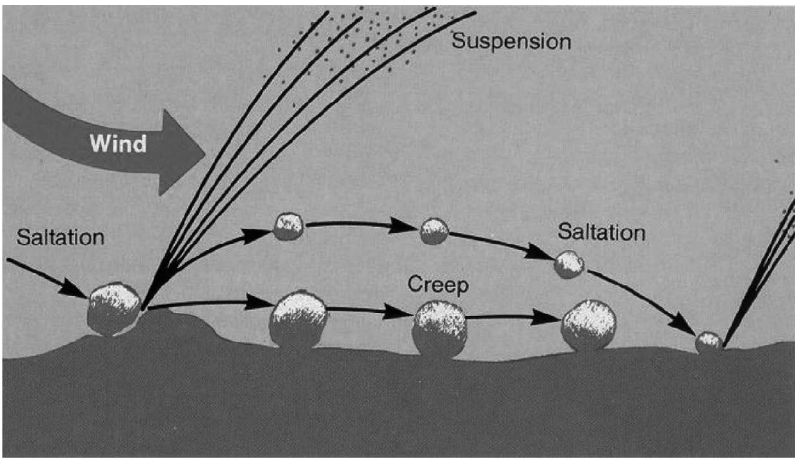


**Figure 2** Erosion processes that are mathematically simulated by the WEPS model to estimate daily soil loss by wind (adapted from Hagen et al. 1996).

**Table 2** Effect of corn residue removal on soil aggregate size distribution after four, two-year corn-soybean production cycles near Brookings, SD (adapted from Hammerbeck et al. 2012).

| Residue Removal | Dry Aggregate Size Classification (mm) | | | | | Erodible Fraction† |
|---|---|---|---|---|---|---|
| | < 0.4 | 0.4–0.8 | 0.8–2.0 | 2–19 | > 19 | g kg$^{-1}$ |
| None | 59 C‡ | 34 C | 75 B | 416 | 416 A | 93 C |
| Moderate | 91 B | 54 B | 105 A | 403 | 347 B | 145 B |
| High | 116 A | 68 A | 118 A | 398 | 300 B | 184 A |
| P > F | 0.0004 | <0.0001 | 0.0006 | NS | 0.0378 | 0.0048 |

†The wind erodible fraction is the mass of soil < 0.84 mm in diameter
‡Numbers followed by the same letter within each aggregate size group are not significantly different at $\alpha = 0.05$ using the Tukey Test

highly erodible fraction increases while the fraction of large aggregates (> 19 mm) decreases, presumably due to lack of carbon input to help build more stable and therefore wind erosion resistant aggregates.

## *Soil Fertility Effects*

Harvesting corn residue for biofuel feedstock or other bioproducts removes not only carbon needed to sustain soil biological and physical attributes, but also several essential plant nutrients. Recent studies by Karlen et al. (2011) showed as expected that nutrient removal was directly proportional to the amount of stover harvested. They showed that average N-P-K removal was increased by 26, 3 and 30 lb ac$^{-1}$ for continuous corn and 37, 3, and 30 lb ac$^{-1}$ for rotated corn, respectively, when compared to harvesting only the grain. There were also increases in secondary (Ca, Mg, and S) and micronutrient (Cu, Fe, Mn, Zn) removal compared to a grain-only harvest.

The increased nutrient removal associated with corn stover harvest could be beneficial if soil test values were extremely high from prior animal manure or fertilizer application rates, but if they needed to be replaced to prevent long-term nutrient depletion, the replacement cost for those nutrients is a factor that must be included when placing a monetary value on the stover. Obviously, fertilizer price is a major and everchanging factor and those values are closely associated with petroleum and transportation costs. Karlen et al. (2011) discussed how the estimated nutrient replacement costs fluctuated throughout five years and acknowledged that they will continue to do so throughout the future. However, one of the most consistent results from their work was in total nutrient replacement cost (~ $17.25 ± $1 ton$^{-1}$). They concluded that having documented such a consistent value makes it more feasible to determine a fair market value for both feedstock producers and consumers.

### *Water Quality and Quantity Effects*

One of the primary environmental concerns for both grain and cellulosic ethanol production from corn continues to be the long-term effects on surface and groundwater quality (UCS 2010a, 2010b, 2011). This concern arose because as the amount of corn grown for ethanol rose from approximately 5 to 40% during the past decade, the use of fertilizer and other inputs to support the crop also increased. This raises environmental concerns because most of the US corn crop is grown in the Mississippi River watershed, which is a major contributor of nitrogen and phosphorus to the Gulf of Mexico and thus a factor creating a "dead zone" where fish cannot survive. Since corn production accounts for 42% of US N fertilizer use, more intensive corn production increases the potential for even greater N loss to surface and groundwater resources.

In addition to water quality impacts, water quantity has also been raised as a concern associated with corn ethanol. Karlen (2011) stated that to understand the complexity of predicting biofuel effects on water quantity and quality, we must first step back from biofuels production *per se* and examine the global hydrologic cycle. Currently, the US uses approximately 48% of its fresh and weakly saline water for thermoelectric power generation, but evaporation and the power generation actually consume only 2 to 3% of this water. The remaining 97 to 98% is returned in its original form and is thus potentially available for reuse. Municipal withdrawals account for another 10%, but nearly 90% of that water is returned as wastewater that can be treated and reused. Finally, industry accounts for another 21% of US freshwater withdrawals, with the quantity and quality of that being returned being industry specific and highly variable.

Agricultural water use differs from use by these other entities in that most of the water is consumed through evapotranspiration (ET) that supports plant growth and development. Water is also consumed when used to leach salts from the soil and thus manage soil salinity. With or without a biofuels industry, agriculture uses large quantities of water. Freshwater extraction ranges from less than 20% to more than 90% for different countries depending upon climate, productivity and water use efficiency (WUE) of the crops being grown. The ratio quantifying the amount of plant dry matter produced for a specific quantity of water used is defined as water use efficiency. The WUE value varies greatly depending on crop species, location, culture practice, climate and weather, and other factors. Growing plants is very water intensive because as much as 1,000 pounds of water may be required to produce just one pound of plant material. Fortunately, the transpired water is recycled in the hydrologic cycle. It falls as precipitation, and after infiltrating into the soil, running off into streams or lakes, or percolating to deeper aquifers, it is once again available for ET in support of plant growth or for other uses. Unfortunately, the groundwater portion of the cycle cannot always be replenished as fast as it is used in many drier regions and as a result groundwater is often irreversibly mined. The Ogallala Aquifer, located in the US Great Plains, is one example where water mining has occurred. A 2009 US Geological Survey (USGS) report stated that in parts of southwest Kansas and the Texas Panhandle, groundwater levels have dropped by more than 150 feet due to intensive crop irrigation and minimal aquifer recharge.

Water is also important for conversion of all feedstocks into biofuels, specifically for heating, cooling, and the chemical processes involved. For the corn-based biofuels conversion process, water consumption has decreased dramatically during the past decade, falling from an average of 5.8 gallons of water per gallon of ethanol in 1998, to 3.0 gallons/gallon or less in 2009. For comparison, the recovery and refining of crude oil requires 3.6 to 7.0 gallons of water per gallon of fuel. Water requirements for conversion of cellulosic materials will depend on the feedstock and the conversion process. These systems are not fully developed, but current estimates of water use range from 1.9 to 6.0 gallons/gallon for ethanol production or 1.0 gallon/gallon for biodiesel (Karlen 2011).

Ultimately, management practices make all the difference with regard to both water quality and quantity issues associated with biofuel production from corn or any other crop. This includes the use of nutrient management plans based on soil property measurements, replacing gullies with grass-filled channels, changing row orientation to follow the contour of the land and adding terraces and grass buffers to control water flow and reduce erosion. Cover crops can be grown from late fall to early spring to capture residual nutrients, add carbon, and protect the soil surface from wind and water erosion. Controlled drainage systems can be used to reduce short-circuiting of nutrients from the soil profile to surface waterbodies.

## Prospects for Overcoming Concerns Regarding the Use of Corn for Biofuels

Using current corn production practices, removing corn residues as a feedstock for ethanol production could and will likely have negative effects on soil and water quality (Wilhelm et al. 2004). However, many of the concerns associated with harvesting corn stover might potentially be eliminated by using alternative crop production practices. The increased use of reduced tillage systems and cover crops would lessen the impact of stover removal on soil erosion and allow more carbon input and less loss from the soil (Perlack et al. 2005). Furthermore, diverting land less well suited to annual crop production to the production of perennial energy crops would address some of the more serious concerns with using corn stover as a bioenergy feedstock. Careful consideration of the ability of the land where the crop is grown to tolerate residue removal could also greatly diminish the overall impact if highly erodible and otherwise unsuitable land is excluded from the practice. Much of this land is either highly erodible or possesses other constraints that make it economically or environmentally marginal for row crop production. By creating a market for cellulosic feedstocks, using corn stover for fuel could lead to the conversion of these lands to more environmentally benign crop management systems (Brick 2011).

Alternative crop production practices to address some of the environmental concerns of harvesting corn stover have already been developed and are being used to a limited extent. The use of no and minimum tillage practices significantly reduces soil erosion and ameliorates loss of soil organic matter (West and Post 2002; Montgomery 2007). This latter effect has a positive impact on carbon sequestration when no-till practices are compared to conventional practices (Bernarcchi 2005). The benefits of no-till agriculture have been studied and known for a several years (Phillips et al. 1980). These include increased soil organic matter and therefore carbon sequestration, reduced fuel and therefore energy requirements, reduced soil erosion, decreased soil compaction, increased water infiltration, improved nutrient cycling, and improved water quality (Reicosky 2008). Despite these advantages, no till production of corn was estimated to be practiced on only 25.5 million acres of cropland in 2009 or about 29.5% of the corn acreage (Horowitz et al. 2010). The main reason no till is not practiced on more acres is the perception of lower yields (Vyn and Raimbult 1991) and returns. Lower yields from no-till corn are often related to later planting date due to slower warming of nontilled soil in spring (Fortin 1993). No-till production also creates a better environment for some crop pests and therefore requires alternative pest management practices. In addition, no-till production requires producers to adopt new production strategies and invest in new farm machinery. This said, creating a market for corn stover, may indeed encourage producers to adopt a no-till strategy in order to compensate for the loss of ecological services provided by the residue when it is left in the field. In the original BTR, production estimates were based on 100% use of no till on crop fields where the residues were being removed as a feedstock in 2030 (Perlack 2005).

The use of cover crops also has potential for reducing the environmental impacts of corn stover removal in some production areas (Fronning et al. 2008). Annual cover crops are generally planted in the fall after a row crop is harvested. They are intended to provide soil cover during the winter period when the ground is normally fallow. Thus, they intercept rainfall and reduce soil runoff reducing erosion and increasing water infiltration. They also hold the soil against wind erosion and thus improve air quality

(Hartwig and Ammon 2002). In the springtime, the actively growing cover crops take up soil nitrogen and immobilize it preventing it from leaching into the groundwater (Mitchell and Tell 1976). The primary obstacles to use of cover crops relate to cost of establishment and timing. The farther north cover crops are planted, the less the time interval is between harvest and the onset of winter weather. In some years, there is little time making their use somewhat risky. To avoid these time constraints researchers and producers have evaluated various methods for establishing cover crops in the standing grain crop using aerial seeding methods. While these methods have shown some success, they are relatively expensive to use and require time to implement. Without a reasonable return to the investment in time and other resources, their use is often hard for producers to justify. However, by allowing harvest of corn stover there may be some financial incentive for using them.

Perennial cover crops are another, although less well developed, option. Research has demonstrated that corn can be grown in the presence of a groundcover and produce yields comparable to conventional production practices (Wiggans et al. 2012). However, it has proven essential to manage competition from the cover crop in the spring with the use of contact herbicides or some other form of suppression (Echtenkamp and Moomaw 1989). Perennial cover crops avoid the establishment and time constraints associated with annual cover crops and essentially provide the same benefits. Additionally, they can have a positive influence on soil moisture because the can increase water infiltration and provide an evaporation barrier in the summer. For this reason, perennial groundcovers are sometimes referred to as living mulches. The use of perennial groundcovers for corn production is not a proven technology, but recent research indicates that it has strong potential for addressing many of the environmental issues associated with corn production and stover removal (Flynn et al. 2013).

Recent increases in the price of corn grain have led producers to alter their crop management practices. Farming land that once produced marginal returns is now profitable and has led to the conversion of this land from pasture or conservation to row-crop production. Unfortunately, much of this marginal land has a disproportionate impact on ecological services that are lost with its conversion to cropland. This is land that is subject to flooding and drought, is highly erodible, or otherwise has inherent characteristics that can lead to negative environmental effects under certain circumstances. Land of this class should not be used for grain production much less with stover removal. The environmental consequences of doing so are disproportionately large compared with the financial gain from doing so. However, development of processing facilities for converting corn stover will create an opportunity for using alternative sources of biomass. Marginal lands could thus be managed productively by growing perennial energy crops such as switchgrass thus preventing or reducing the negative environmental consequences of converting them to cropland.

Developing and implementing this landscape vision for producing biofuels feedstock could facilitate balancing the economic drivers and limiting factors needed to achieve sustainable feedstock supplies and alleviate many concerns regarding the use of corn for biofuels (Fig. 3 and Karlen et al. 2012). The landscape vision would not replace current corn and soybean production systems but rather augment them with several other potential bioenergy feedstocks such as switchgrass, *Miscanthus*, sorghum, mixed cool- and warm-season grasses, or woody species such as poplar or willow. Again, the premise for this vision is that rather than focusing solely on energy production from corn, a diversified landscape would provide multiple ecosystem services such as:

1. Sustainable grain and biomass supplies for food, feed and energy
2. Increased C sequestration
3. Protection of water quality
4. Increased productivity and profitability
5. Reduced producer and environmental risk
6. Greater biodiversity
7. Improved wildlife habitat
8. Vigorous rural community development supported by new industries and entrepreneurial opportunities

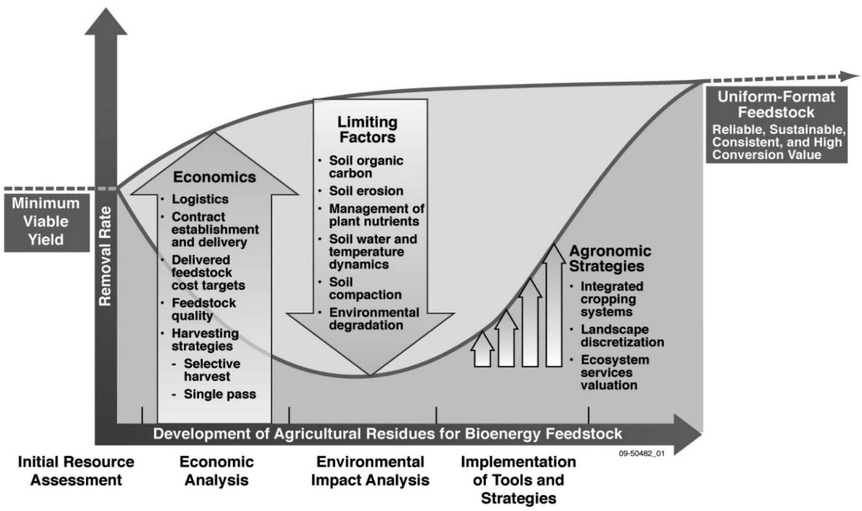


**Figure 3** An illustration of competing economic drivers and limiting factors that must be balanced to achieve sustainable cellulosic feedstock supplies needed to support a transition from fossil to renewable fuels (from Wilhelm et al. 2010).

The advanced biofuel production systems associated with this landscape vision should not be viewed as limited to ethanol or any other specific fuel source. In addition to starch from the corn grain *per se*, the crop may be able to efficiently contribute additional feedstock in the form of crop residues or even by removing the pericarp before fermentation. Extraction of oil from the distiller's grain is another component of the complete system. Furthermore, the use of these additional components from the corn crop may even produce a fuel that qualifies as an advanced biofuel and, depending on the conversion process and to a large part on the soil organic carbon (SOC) dynamics associated with the entire system.

A starting point for implementing the landscape vision is to establish best management practices and standards for the entire biofuel industry. These practices should address all of the limiting factors and be supported by the improved agronomic practices that are being developed to ensure supplies for conversion facilities can be met (Fig. 3). A current example of this approach is the developmental work being done by the Council for Sustainable Biofuel Production (CSBP), which is striving to develop standards that would enable those purchasing bioenergy feedstock to appropriately compensate land owners and operators not only for the commodities *per se*, but also the ecosystem services their land provides. This could also help overcome the perception that using land for biofuel production is in direct competition with using if for food and feed production, thus confirming a point made by Rosillo-Calle and Johnson (2010) that the issue is not land availability but rather how the land is managed.

In summary, there are ample opportunities to use corn as the foundation for a viable biofuel industry in the Midwestern US. The key is management and not focusing solely on corn grain as the only feedstock. Diversity is crucial and the use of best management practices is essential. In other words, all options are open.

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