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Review

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# Managing and enhancing switchgrass as a bioenergy feedstock†

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Abstract: The United States Department of Energy (DOE) has identified switchgrass (*Panicum virgatum* L.) as a viable perennial herbaceous feedstock for cellulosic ethanol production. Although switchgrass bioenergy research was initiated by USDA-ARS, Lincoln, NE, USA in 1990, switchgrass research has been conducted at this location since the 1930s. Consequently, a significant amount of genetic and agronomic research on switchgrass has been conducted for the Corn Belt and Central Great Plains of the USA that is directly applicable to its use as a biomass energy crop. Similar research must be conducted in other major agroecoregions to verify or modify switchgrass management practices (agronomics) for bioenergy production. The technology to utilize switchgrass for producing ethanol using a cellulosic platform or by pyrolysis to generate syngas is advancing rapidly. Regardless of platform, using switchgrass for ethanol production will require the development of improved bioenergy cultivars or hybrids and improved agronomics to optimize production and will introduce competing uses for the land base. Published in 2008 by John Wiley & Sons, Ltd

Keywords: bioenergy; biomass; cellulosic ethanol; renewable energy

Abbreviations: C, carbon; DM, dry matter; N, nitrogen; SOC, soil organic carbon.

## Introduction

The demand for US-finished motor gasoline increased by more than 27 million US gallons per day from 2001 to 2006.[1] Alternative transportation fuels coupled with a reduction in energy consumption are needed to address this demand. Although numerous energy alternatives to fossil fuel exist, a sustainable ethanol production system works well with existing automobile standards, has consumer acceptance, is renewable, and reduces dependence on oil imports. The large-scale use of ethanol for transportation fuel will require cellulosic ethanol technology.[2]

Switchgrass is not a one-size-fits-all bioenergy feedstock. Herbaceous perennials such as alfalfa (*Medicago sativa* L.), bermudagrass [*Cynodon dactylon* L. (Pers.)], Miscanthus (Miscanthus x giganteus), napiergrass (*Pennisetum purpureum* Schumach.), and reed canarygrass (*Phalaris arundinacea* L.) have the potential to be perennial feedstocks

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in different regions of the United States based on climatic and land availability variables.[3,4] Of these species, switchgrass is the only North American native and is well adapted to marginal croplands, similar to land enrolled in the Conservation Reserve Program (CRP). Perennials, such as switchgrass, have advantages over annual crops for cellulosic biomass because they do not have the annual establishment requirements with associated economic and net energy inputs; they require fewer chemical inputs (herbicide and fertilizer) than annual row crops; they produce large quantities of biomass; and they provide important ecosystem services. Herbaceous perennials do require some level of input to optimize productivity and maintain stand quality.

Current switchgrass research is focusing on breeding and genetics to improve biomass and energy yields per unit of land area and improved conversion efficiency and agronomics which includes establishment, fertility management, weed control, and harvest and storage management, and documentation of the value of ecosystem services. Additional research on developing management practices that maintain quality stands over multiple years of harvest, optimize biomass and net energy yield, optimize economic return for producers, and provide beneficial environmental services such as erosion control and C sequestration will enhance the value of using switchgrass for biomass energy. On January 31, 2006, the President of the United States in his State of the Union Address said, 'We must also change how we power our automobiles. We will increase our research in better batteries for hybrid and electric cars, and in pollution-free cars that run on hydrogen. We'll also fund additional research in cutting-edge methods of producing ethanol, not just from corn, but from wood chips and stalks, or switchgrass. Our goal is to make this new kind of ethanol practical and competitive within six years.'[5] This single event accelerated switchgrass research efforts, including the first significant research investments in switchgrass by private companies, particularly in the area of molecular genetics.

Switchgrass is a potential bioenergy feedstock because it is broadly adapted and has high yield potential on marginal croplands.[6,7] This perennial $C_4$ grass is native to North America except for the areas west of the Rocky Mountains and north of 55° north latitude.[7] This broad latitude of origin affects yield potential and survival under environmental extremes.[8] Switchgrass will be productive in most rain-fed production systems receiving at least 600 mm of annual precipitation, east of the 100th Meridian.

Several recent reviews have been conducted on switchgrass as a biomass feedstock.[7,9–12] In the current review we address the feasibility and production challenges of using switchgrass for bioenergy, emphasizing our experiences in the central Great Plains and Midwest USA.

## Switchgrass germplasm

To date, no switchgrass cultivars have been developed and released specifically for use as a bioenergy feedstock. Most of the research information used for evaluating switchgrass as a bioenergy feedstock is based on cultivars developed for livestock forage. Switchgrass breeding programs have focused on improving establishment, forage yield and quality, and insect and disease resistance.[7] For example, 'Trailblazer' and 'Shawnee' were released by the USDA-ARS and the University of Nebraska and are the only switchgrass cultivars developed with improved forage quality[7] and likely increased ethanol conversion potential, and are among the highest biomass-yielding upland cultivars throughout the Great Plains and Midwest. Trailblazer and Shawnee will likely be planted on a large portion of the first generation of dedicated switchgrass feedstock production fields on marginal sites in the Great Plains and Midwest states.

Breeding switchgrass for use as a bioenergy feedstock is focusing on many of the same characteristics, with an emphasis on increasing biomass yield. A potential mechanism for increasing biomass yield is by producing F1 hybrid cultivars based on the upland and lowland ecotypes[13] (see section on Opportunities). Current research by the authors indicates hybrid cultivars can increase biomass yield by more than 40% compared to the parental lines. Public availability of these hybrid lines will not occur for at least 10 years.

## Establishing and managing switchgrass

Poor stand establishment can delay acceptable switchgrass production by one or more years.[14] Planting seed too deeply and competition from grassy and broadleaf weeds are major reasons for switchgrass establishment delay and stand failure.[7,15] Switchgrass seeding rates for forage production range from 200 to 400 pure live seed (PLS) $m^{-2}$,[16] and seed should be planted at a depth of 1 to 2 cm.[7] Herbicidal control of weeds improves switchgrass establishment success.[7] Switchgrass establishment is best determined by stand frequency of occurrence.[17] A stand frequency of 50% or greater indicates a successful stand, whereas stand frequency from 25 to 50% is marginal to adequate, and stands with less than 25% frequency indicate a partial stand that may need re-seeding.[17] In a study conducted on 10 farms in Nebraska, South Dakota, and North Dakota, switchgrass fields with stand frequency of 40% or greater provided a successful establishment year stand threshold for subsequent post-planting year biomass yields.[14] Successful stand establishment during the seeding year is mandatory for economically viable switchgrass bioenergy production systems.[18]

Switchgrass stands have been successfully established by seeding during spring, early summer, and autumn. Planting switchgrass in mid-March in Nebraska has been suggested to be superior to planting in late April and May.[19] Seeding during late autumn has been used as a strategy to subject seeds to natural cold stratification to break seed dormancy and potentially improve stand establishment. However, planting 3 weeks before or after the recommended maize planting date[20] has been a reliable general planting date recommendation for switchgrass.[7]

Applying 2,4-D (2,4-dichlorophenoxyacetic acid) after switchgrass seedlings have approximately four to five leaves is the most cost-effective method for controlling broadleaf weeds in switchgrass fields.[7] Atrazine [6-chloro-N-ethyl-N'-(1-methylethyl)-1,3,5-triazine-2,4-diamine] has improved switchgrass establishment by controlling broadleaf weeds and cool-season grassy weeds, [21,22] but it does not control warm-season annual grassy weeds. Pre-emergence application of imazethapyr (Pursuit®[1]; 2-[4,5-dihydro-4-methyl)-4-(1-methylethyl)-5-oxo-1H-imidazol-2-yl]-5-ethyl-3-pyridinecarboxylic acid) provided excellent weed control and enabled switchgrass to be fully established within one year after planting.[23] The post-plant, pre-emergence application of a tank mix of quinclorac (Paramount®; 3,7-Dichloro-8-quinolinecarboxylic acid) plus atrazine has provided excellent weed control in switchgrass seedings in Nebraska, North Dakota, and South Dakota (Mitchell, unpublished data). The labeled use of imazethapyr and quinclorac on switchgrass as a pre- or post-emergent herbicide varies with state or region and year. The efficacy of these herbicides does not change, only the regulations. Herbicide labels for these and other herbicides must be checked each year and followed. A successfully established stand will likely require no or only periodic, limited additional herbicide applications in the post-establishment years to control weed problems. Well-managed stands usually have limited weed pressure.

Optimizing switchgrass biomass yields and maintaining quality stands requires fertilizer inputs. Switchgrass tolerates low fertility soils but responds to applied nitrogen (N). The amount of applied N required by switchgrass is a function of the yield potential of the site, productivity of the cultivar, and management practices such as time of harvest.[24] The optimum N rate for Alamo switchgrass, a lowland cultivar, managed for biomass yield in Texas was 168 kg N $ha^{-1}$, and biomass yield averaged 14.5 and 10.7 Mg $ha^{-1}$ $yr^{-1}$ at Stephenville and Beeville, respectively.[25] Biomass production declined over years without applied N, and was sustainable only with the application of at least 168 kg N $ha^{-1}$ $yr^{-1}$. In Alabama, Ma *et al.*[26] reported switchgrass yields increased as N rate increased up to 224 kg N $ha^{-1}$.

Switchgrass biomass increases as N rate increases, but the potential for N to leach out of the root zone and contaminate groundwater is a concern. In South Dakota Conservation Reserve Program (CRP) lands dominated by switchgrass, the application of 56 kg N $ha^{-1}$ increased total biomass, but there was no benefit to applying more N.[27] In Nebraska and Iowa, biomass yields of 'Cave-In-Rock' switchgrass, an upland cultivar, increased as N rate increased from 0 to 300 kg N $ha^{-1}$, but residual soil N increased when more than 120 kg N $ha^{-1}$ was applied.[24] Biomass production was optimized with the application of 120 kg N $ha^{-1}$, with approximately the same amount of N being applied as was being removed by the crop. They concluded that N fertilizer recommendations in this region should be based on anticipated biomass yield, with approximately 10 to 12 kg $ha^{-1}$ $yr^{-1}$ of applied N is needed for each 1 Mg $ha^{-1}$ of biomass yield.[24] For example, harvesting a

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[1] Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the US Department of Agriculture.

switchgrass field producing 11 Mg ha$^{-1}$ of DM with a crude protein concentration of 7.5% (1.2% N) will remove about 130 kg of N ha$^{-1}$. Because of the soil mineralization potential of some soils, atmospheric N deposition, residual soil N from previous crops that may be distributed deep in the soil profile, and the deep-rooting capability of switchgrass, soil samples for determining available soil N for switchgrass production must be taken to a depth of 1.5 to 2 m. Fertilizer application rates should be based on the difference between the crops' needs and available soil N.

Switchgrass response to phosphorus (P) has been variable. Switchgrass did not respond to applied P in Texas[25] or in low P soils in Iowa.[28] However, research in Nebraska suggested switchgrass may respond to applied P if P availability in the soil is low.[29,30] The response of switchgrass to other mineral elements is largely uninvestigated and remains a major research need in most areas where switchgrass potentially will be grown as a bioenergy crop.

## Harvesting switchgrass for bioenergy

Maximizing dry matter (DM) production is the primary objective when harvesting switchgrass for bioenergy. A single harvest during the growing season at a 10-cm stubble height typically maximizes switchgrass biomass recovery and maintains stands (Fig. 1). Sanderson *et al.*[31,32] harvested several switchgrass strains once or twice per growing season from multiple environments in Texas. They concluded that 'Alamo' was the best adapted commercially available switchgrass cultivar for biomass feedstock production in Texas, and that a single harvest in autumn maintained stands and maximized biomass production. Yields ranged from 8 to 20 Mg ha$^{-1}$ yr$^{-1}$, and soil organic carbon (SOC) increased by 42%, indicating that switchgrass grown for bioenergy has good potential for storing SOC in Texas.

Figure 1. This field of Shawnee switchgrass was no-till drilled into soybean stubble in May 2006, harvested to a 10-cm stubble height on July 30, 2007, and produced 9 Mg ha$^{-1}$ of dry matter.

In South Dakota CRP lands dominated by switchgrass, Mulkey *et al.*[27] recommended applying 56 kg N ha$^{-1}$ in the spring and harvesting once after a killing frost to maintain stands and optimize biomass production. In North Dakota, Frank *et al.*[33] applied 67 kg N ha$^{-1}$ in the autumn and harvested at the soil level for a 3-year average biomass yield of 6.4 and 9.1 Mg ha$^{-1}$ for the upland cultivars Dacotah and Sunburst, respectively.

An intensive harvest management study consisting of either one or two harvests per year was conducted in Nebraska and Iowa.[24] Optimum biomass yields of 'Cave-In-Rock' were attained with a single harvest during anthesis (R3 to R5).[24] Biomass yields ranged from 10.5 to 12.6 Mg ha$^{-1}$ yr$^{-1}$, and quality stands were maintained throughout the study by harvesting during anthesis. These studies indicate that a single annual harvest will optimize efficiency in the central United States, but harvest timing needs to be considered for stand maintenance and potentially optimizing cellulosic ethanol yield. Harvest strategies may vary for upland and lowland ecotypes, which have not been compared in agroecoregions where both ecotypes will be grown.

An alternative approach where switchgrass was harvested in autumn after a killing frost or was left standing over winter and harvested in spring was evaluated in Pennsylvania.[34] Delaying switchgrass harvest until spring reduced yield by 20 to 24% compared with harvesting in autumn after a killing frost.[34] Delaying harvest had no effect on energy yield from gasification. Although losing 20% of total yield is significant, this may be acceptable on conservation lands where standing biomass could provide winter wildlife cover, and spring harvest would minimize direct impacts during the nesting season.[34]

Limited research has been conducted on DM losses during switchgrass harvest and storage. In Texas, DM losses during large, round baling ranged from 1 to 5%, with larger losses occurring with drier material.[35] Switchgrass bales stored for 6 or 12 months inside had 0 to 2% DM losses, whereas bales stored outside lost 5 to 13% of the original bale weight.[35] Switchgrass bales stored unprotected outside lost up to 11% of ethanol extractables, which could significantly reduce conversion to ethanol.[36] In Pennsylvania, harvesting switchgrass in the autumn compared to allowing the dormant material to stand over winter and harvesting in the spring resulted in a 40% loss of DM, primarily because the spring harvest left more material behind by the baler.[34] Although we have not measured DM losses during baling in our studies in Nebraska, more shattered leaf material remains on the ground under the windrow following baling in November compared to baling in August. An alternative to baling is to reduce the particle size by chopping switchgrass in the field and storing as an air-dried and chopped material (Fig. 2). Chopping the switchgrass in the field may serve as a form of value-added pre-processing to reduce the energy requirements, and therefore costs, for grinding the feedstock to its final particle size requirement. Additionally, chopping has lower estimated costs than baling or pelleting.[37] Densification may be an issue for efficiently storing and transporting this material, which could be overcome by modulizing the chopped material.[37]

Figure 2. This field of Shawnee switchgrass was harvested to a 10-cm stubble height and chopped with a silage chopper equipped with a pick-up head in November.

## Ethanol production potential, energy balance, and economics

Cellulosic ethanol production has been achieved at the experimental and pilot scale. For background on the conversion process, see Jorgensen *et al.*[38] Consequently, cellulosic ethanol conversion is based on estimated values. Dien *et al.* evaluated alfalfa stems, reed canarygrass, and switchgrass at different maturities to determine their bioconversion potential.[4] Maturity of switchgrass biomass influenced biomass quality and potential glucose recovery for ethanol fermentation.[4] As switchgrass maturity increased, carbohydrates increased, lignin concentration increased, and glucose recovery decreased, likely due to the elevated lignin concentration. This indicates a harvest maturity exists that optimizes DM production and ethanol conversion potential for switchgrass, and that switchgrass feedstock quality will need to be monitored in the feedstock delivery stream.

The potential change in marginal land use associated with switchgrass production could exceed 10%, depending on the yield potential of the switchgrass strains (see Production Challenges below), making it important to understand the feasibility and production potential of marginal sites. In a 5-year study in Nebraska, the potential ethanol yield of switchgrass averaged 3474 L ha$^{-1}$ and was equal to or greater than the potential ethanol yield of no-till corn (grain + stover) on a dry-land site with marginal soils.[39] Removing an average of 51% of the corn stover each year reduced subsequent corn grain yield, stover yield, and total biomass yield. Growing switchgrass on these marginal sites will likely enhance ecosystem services more rapidly and significantly than on more productive sites.

The energy efficiency and sustainability of ethanol produced from grains and cellulosics has been evaluated using net energy value (NEV), net energy yield (NEY), and the ratio of the biofuel output to petroleum input [petroleum energy ratio (PER)].[40] Energy produced from new carbon sources is held to a different standard than energy produced from fossil fuels, in that renewable fuels must have highly-positive NEV and NEY. An energy model using estimated agricultural inputs and simulated biomass yields predicted switchgrass could produce greater than 700% more output than input energy.[2] A recent field-scale study using known farm inputs and actual harvested switchgrass yields conducted on 10 farms over 5 years in Nebraska, South Dakota, and North Dakota determined switchgrass produced 540% more renewable than non-renewable fuel consumed.[40] The estimated on-farm NEY was 60 GJ ha$^{-1}$ y$^{-1}$,[40] which was 93% greater than human-made prairies and 652% greater than low-input switchgrass grown in small plots in Minnesota.[41] The 10 farms and five production years had a PER of 13.1 MJ of ethanol for every MJ of petroleum input, and produced 93% more ethanol per ha than human-made prairies and 471% more ethanol per ha than low-input switchgrass in Minnesota.[40] In simulated production trials in Wisconsin, switchgrass produced the most net energy, followed by an alfalfa-corn rotation and then continuous corn.[42] Managing switchgrass for bioenergy is an energetically positive and environmentally sustainable production system for the central Great Plains and Midwest.

Switchgrass is an economically feasible source for cellulosic ethanol. A recent field-scale study using known farm inputs and actual harvested switchgrass yields conducted on 10 farms over 5 years in Nebraska, South Dakota, and North Dakota determined switchgrass could be delivered at the farm gate for \$54 Mg$^{-1}$.[18] They concluded that the development of new cultivars, improved production practices, and an expanded market for switchgrass will reduce the farm-gate cost.[18] They expect that large quantities of switchgrass could be delivered at the farm gate for \$40 to \$45 Mg$^{-1}$.[18] Assuming a switchgrass farm-gate cost of \$40 to \$54 Mg$^{-1}$ and conversion of 0.329 liters of ethanol per kg of switchgrass, the farm-gate feedstock cost would range from \$0.12 to \$0.16 per liter.

## Ecosystem services

The perennial root system of switchgrass provides two important ecosystem services; protecting soil from wind and water erosion, and sequestering C in the soil profile.[43] Frank *et al.*[33] reported that soil C increased at a rate of 1.01 kg C m$^{-2}$ yr$^{-1}$, and switchgrass plantings in the northern Great Plains have the potential to store significant quantities of SOC. Liebig *et al.*[43] reported that switchgrass grown in North Dakota stored 12 Mg ha$^{-1}$ more SOC in the 30 to 90 cm depth than a cropland paired field experiment. They concluded that switchgrass effectively stores SOC not just near the soil surface, but at greater depths where C is less susceptible to mineralization and loss. Lee *et al.*[44] reported that switchgrass grown in South Dakota CRP stored SOC at a rate of 2.4 to 4.0 Mg ha$^{-1}$ yr$^{-1}$ at the 0 to 90 cm depth. In a 5-year study conducted on 10 farms in Nebraska, South Dakota, and North Dakota, average greenhouse gas (GHG) emissions from switchgrass-based ethanol were 94% lower than estimated GHG emissions from gasoline.[41] In addition to increasing soil carbon (C), growing switchgrass may increase wildlife habitat, increase landscape and biological diversity, increase farm revenues, and return marginal farmland to production.[45–48] Not harvesting some switchgrass each year would increase the habitat value for grassland bird species that require tall, dense vegetation structure.[47]

## Production challenges

Using switchgrass as a feedstock for cellulosic ethanol production provides several challenges. First, ethanol plants require a reliable and consistent feedstock supply, and the cellulosic ethanol plant feedstock supply logistics are daunting. A 300 million liter (80 million gallon) per year plant will require 907 000 DM metric tons (one million US tons) of feedstock per year assuming 330 liters of ethanol can be produced from one metric ton of feedstock (80 gallons per US ton). Although a cellulosic ethanol plant likely will utilize multiple feedstocks, a single feedstock platform will be assumed for this discussion. Operating every day of the year, the plant will require 2490 DM metric tons of feedstock per day, or 222 hectares of switchgrass yielding 11.2 DM metric tons per hectare. If a loaded semi can deliver 30 round bales each containing 0.55 DM metric tons (18 US tons), the ethanol plant will use 152 semi loads of feedstock per day, requiring a semi to be unloaded every 9.5 minutes 24 hours per day, 7 days per week.

Second, the local agricultural landscape must have an adequate available land base to produce feedstock. The potential DM production and ethanol yield of the feedstock will determine the total land area required for feedstock production. Assuming 48 km is the maximum economically feasible distance feedstock can be transported, all of the feedstock must be grown within a 48-km radius of the biorefinery, an area containing about 723 823 ha. Using our previous assumptions, a 300-million-liter-per-year cellulosic ethanol plant would require 907 000 metric tons of switchgrass feedstock per year. If 2.24 DM Mg/ha (1 US ton/acre) of feedstock was produced, 404 686 ha (55% of the land base) would be needed for feedstock production, and is not feasible in most agricultural areas. At 11.2 Mg/ha (5 US tons/acre), a commonly achieved yield with available forage cultivars, only 11% of the land base would be needed for feedstock production, and is feasible in most agricultural areas. However, if our current switchgrass yield goal of 22.4 DM Mg/ha is attained in the central Great Plains and Midwest at the field scale (we have achieved these yields in small plot research) only about 40 470 ha (5.5% of the land base) would be needed for feedstock production, and would minimally alter the agricultural landscape. These calculations reinforce the importance of high DM yield potential to the agricultural feasibility of cellulosic ethanol, not to mention the inability of the producer to profit by growing low-yielding energy crops. A majority of the switchgrass likely will be grown on marginal lands that have suboptimal characteristics (i.e., slope, soil depth, etc.) for producing food and feed, or on lands currently enrolled in conservation programs. The Midwest and central Great Plains are areas that can be used to meet the US food, feed, and bioenergy requirements because of its large suitable land base and climatic conditions.

Third, for the producer, switchgrass production must be profitable, it must fit into existing farming operations, it must be easy to store and deliver to the ethanol plant, and extensive efforts must be made to inform producers on the agronomics and best management practices for growing perennial herbaceous energy crops. Using switchgrass for bioenergy provides unique opportunities for cultural change, operational diversification, and large-scale biodiversity on the agricultural landscape. Switchgrass cropping systems can provide several environmental benefits compared to annual crops such as stabilizing soils and reducing soil erosion, improving water quality, increasing and improving wildlife habitat, and storing C to mitigate greenhouse gas emissions.[44,47,48] However, agronomic and operational aspects of switchgrass production systems must be developed and accepted by farmers.[50] Switchgrass fits well into the production systems of most farmers. Harvesting switchgrass near the first of August is a time when most farmers have few competing production practices, and handling switchgrass as a hay crop is not foreign to most producers. Most producers likely will be attracted by the economic opportunities presented by switchgrass for small, difficult to farm, or poorly productive fields.

## Potential difficulties

There are potential difficulties with large-scale production of switchgrass monocultures, but most are speculation at this point. Concerns arise for potential disease and insect pests associated with the production of millions of hectares of switchgrass, especially since little research has been conducted in these areas. Most pathogen issues cannot be fully realized until large areas are planted to switchgrass. However, the long-term exposure of switchgrass to pathogens native to North America, the broad genetic background, and the initial pathogen screening conducted during cultivar development will likely limit the negative impacts of native pests.

## Opportunities

Switchgrass is a polymorphic species with two distinct ecotypes, lowland and upland, and two ploidy levels, tetraploid (36 chromosomes) and octaploid (72 chromosomes).[7] Lowland ecotypes are found on flood plains and other areas that receive run-on water, whereas upland ecotypes occur in upland areas that are not subject to inundation.[7] Most switchgrass cultivars that were previously developed for pastures were upland types because they generally have smaller stems and generally more leaves per square meter. The lowland ecotypes, because of their higher yield potential, may be most suitable for biomass energy production. Switchgrass is photoperiod sensitive so cultivars need to be developed for different plant hardiness zones or plant adaptation regions.[51,52] All lowland ecotypes are tetraploids whereas upland ecotypes have both ploidy levels. Tetraploid upland and lowland crosses are fertile and viable but octaploid x tetraploid crosses are not.[7,13,53] Switchgrass plants are largely self-incompatible and in nature or in seed production fields are cross-pollinated by wind.[7,13,53] Because of their reproductive system, most cultivars released to date have been developed using population improvement breeding systems. These breeding systems have increased yield performance of switchgrass by 20 to 30% from existing parent types.[10] It is feasible to use the self-incompatibility system to produce F1 hybrid cultivars of lowland and upland parents which could result in additional yield improvements.[13,53]

Conventional plant breeding and molecular genetics techniques provide opportunities for improving switchgrass for bioenergy. Switchgrass breeding programs have focused on improving establishment capability, forage yield and quality, and insect and disease resistance.[7] Breeding for improved forage *in vitro* dry matter digestibility (IVDMD) has increased average daily gains of beef cattle (*Bos taurus*) grazing switchgrass pastures in comparison to older cultivars,[54] and has resulted in the release of Trailblazer and Shawnee, the only switchgrass cultivars developed with improved forage quality.[7] Additionally, populations of other warm-season perennial grasses such as big bluestem (Andropogon gerardii Vitman.) have been developed with improved forage digestibility that also has significantly improved average daily gains.[55,56]

Breeding for high IVDMD or comparable cellulosic biorefinery traits will likely increase fermentable substrates for ethanol production.[57] Cellulose and hemicellulose provide the fermentable substrates in switchgrass, but lignin can interfere with the conversion process. Consequently, increasing cellulose and hemicellulose and decreasing lignin are logical approaches to increasing ethanol yield from switchgrass. Breeding for high IVDMD resulted in a linear increase in IVDMD and linear decrease in lignin concentration.[58] Reducing lignin concentration in some switchgrass families reduced winter survival,[7,59] but reduction in winter survival did not occur in populations in which selection was also practiced for biomass yield which is correlated with fitness.[60] However, lignin in switchgrass biomass is not all bad. Lignin is combustible and the high lignin material remaining after fermentation can be used in a biorefinery as a fuel source for distillation and the production of electricity.[2] Breeding for increased tiller density, phytomer number per tiller, and phytomer mass may provide opportunities for increasing yield, especially in lowland ecotypes.[61] Genetics and breeding efforts to increase both biomass yield and biorefinery conversion potential will result in cultivars and hybrids with significantly increased liquid fuels yield potential per land area. Improved management practices should enable farmers to profitably optimize the bioenergy yield potential of the improved plant materials. Additionally, new conversion technologies are emerging at a rapid pace, and may change the direction of cellulosic bioenergy production.

## Conclusion

Enhancing switchgrass feedstock production will require advancements in agronomics as well as genetics. Consequently, research effort must find a balance between basic and applied genetics in conjunction with agronomics, or the full potential of genetic improvements will not be realized. Additionally, scientists must provide society with accurate information to understand the broad-reaching value of renewable energy. We can determine the economic value of switchgrass in terms of DM yield per land area, quantity of ethanol produced per land area, and weight of C sequestered in a land area. However, the total value of switchgrass as a biomass feedstock is difficult to quantify. How do we place a dollar value on sustainable energy production, soil stabilization, water quality improvement, habitat enhancement for grassland birds, or energy security? These will be important environmental, social, and political considerations as the production of renewable fuel sources moves forward.

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