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Large-scale production, harvest and logistics of switchgrass (*Panicum virgatum L.*) – current technology and envisioning a mature technology

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Abstract: Switchgrass (*Panicum virgatum L.*) is a promising cellulosic biomass feedstock for biorefineries and biofuel production. This paper reviews current and future potential technologies for production, harvest, storage, and transportation of switchgrass. Our analysis indicates that for a yield of 10 Mg ha^{-1}, the current cost of producing switchgrass (after establishment) is about \$41.50 Mg^{-1}. The costs may be reduced to about half this if the yield is increased to 30 Mg ha^{-1} through genetic improvement, intensive crop management, and/or optimized inputs. At a yield of 10 Mg ha^{-1}, we estimate that harvesting costs range from \$23.72 Mg^{-1} for current baling technology to less than \$16 Mg^{-1} when using a loafing collection system. At yields of 20 and 30 Mg ha^{-1} with an improved loafing system, harvesting costs are even lower at \$12.75 Mg^{-1} and \$9.59 Mg^{-1}, respectively. Transport costs vary depending upon yield and fraction of land under switchgrass, bulk density of biomass, and total annual demand of a biorefinery. For a 2000 Mg d^{-1} plant and an annual yield of 10 Mg ha^{-1}, the transport cost is an estimated \$15.42 Mg^{-1}, assuming 25% of the land is under switchgrass production. Total delivered cost of switchgrass using current baling technology is \$80.64 Mg^{-1}, requiring an energy input of 8.5% of the feedstock higher heating value (HHV). With mature technology, for example, a large, loaf-collection system, the total delivered cost is reduced to about \$71.16 Mg^{-1} with 7.8% of the feedstock HHV required as input. Further cost reduction can be achieved by combining mature technology

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with increased crop productivity. Delivered cost and energy input do not vary significantly as biorefinery capacity increases from 2000 Mg d^{-1} to 5000 Mg d^{-1} because the cost of increased distance to access a larger volume feedstock offsets the gains in increased biorefinery capacity. This paper outlines possible scenarios for the expansion of switchgrass handling to 30 Tg (million Mg) in 2015 and 100 Tg in 2030 based on predicted growth of the biorefinery industry in the USA. The value of switchgrass collection operations is estimated at more than $0.6 billion in 2015 and more than $2.1 billion in 2030. The estimated value of post-harvest operations is $0.6–$2.0 billion in 2015, and $2.0–$6.5 billion in 2030, depending on the degree of preprocessing. The need for power equipment (tractors) will increase from 100 MW in 2015 to 666 MW in 2030, with corresponding annual values of $150 and $520 million, respectively.

Keywords: switchgrass; harvest and collection; logistics, IBSAL, handling and pre-processing; transport; supply chain and logistics; cost, energy and emissions

Introduction and objectives

Switchgrass (*Panicum virgatum L.*) is a perennial, warm-season grass, native to North America. It grows east of the Rocky Mountains in the USA, from the warm southern region to the Great Plains and northern climates of Canada. After establishment, the stand can be productive for 10 years or more. Switchgrass can adapt to marginal lands, and tolerates soil water deficits and low soil nutrient concentrations. Upland varieties usually grow 1.5 to 1.8 m tall and are better adapted to well-drained soils in mid to northern latitudes. Lowland varieties grow up to 3.7 m tall and are typically adapted to lower latitudes and moist locations.[1] In their summary of production data, McLaughlin and Kszos[2] reported that average yields ranged from 4.5 Mg ha^{-1} in the northern plains to 23.0 Mg ha^{-1} in Alabama, with the overall US average being 11.2 Mg ha^{-1}. McLaughlin *et al.*[6] suggest that the current US average yield can possibly be doubled and even tripled by 2025 (Table 1). They established a yield baseline for year 2004 by applying a 30% discount on published yield. This 30% was to account for any overestimation of field-scale yields by smaller research plots. They used the crop production model ALMANAC to predict switchgrass yield for 9 agricultural districts and three soil types based on 13 years of weather data. Calculated yield data in Table 1 show that the projected yield in southern regions will be more than 3.5 times the baseline. Projected increase in switchgrass yield in the Corn Belt will be roughly 2.5 times and in other locations around 1.5 times.

Experience with the type of equipment needed for harvesting switchgrass is limited. To date, conventional forage equipment has been used to harvest and package switchgrass when the yield is comparable to that for single-cut hay (i.e., ~ 3 to 8 Mg ha^{-1}). When handling higher yields, the speed of such equipment must be reduced. There have been reports stating the difficulty of baling high-yielding switchgrass[4,5] late in the fall when the crop has dried out. Alternative, specially designed systems would likely increase switchgrass harvest efficiencies and reduce costs.

While considerable research has been conducted on switchgrass production, data for harvesting, storage, and transporting switchgrass on a commercial scale are limited mainly to work by Bransby *et al.*[8] who used a model to estimate effects of switchgrass yield, transportation form (baled, chopped, modulized, or pelletized), hauling distance, and truck capacity. Delivered cost was generally higher for bales and pellets than for chopped material. As yield increased costs in $ Mg^{-1} decreased, but these relationships

Table 1. Projected increase in the yield of switchgrass extracted from McLaughlin *et al.*[6]

US Production region	Baseline yield (2004) (Mg ha^{-1})	Annual gains (y^{-1})	Projected 2030
North-east	10.9	1.5	16.0
Appalachia	13.1	5.0	46.4
Corn Belt	13.4	3.0	28.8
Lake State	10.7	1.5	15.8
South-east	12.3	5.0	43.7
Southern Plains	9.6	5.0	34.2
Northern Plains	7.8	1.5	11.4

were not linear and the added benefits were relatively small above a yield of 16 Mg ha^{-1}. Cost increased linearly with hauling distance and decreased with increased truck capacity, although this relationship was not linear and indicated relatively little benefit when truck capacity increased above 20 Mg. Minimal field data and practical experience are available for harvesting and handling the high yields (15–30 Mg ha^{-1}) and millions of hectares necessary to meet the 30% bioenergy goals of 2030.[7]

Our objective here is to estimate the cost and energy input for raising and harvesting switchgrass using both current equipment and practices, and foreseeable mature technology. The analysis assumes an initial base case yield of 10 Mg ha^{-1}, and then considers projected yields of 20 and 30 Mg ha^{-1}.

Switchgrass production and harvest strategies

Switchgrass is propagated from seed, with a commonly recommended seeding rate of 4 to 10 kg ha^{-1}.[8] In general, 10 to 20 plants m^{-2} will provide an acceptable stand. Switchgrass may take three or more years for stands to become fully established. Seedbed preparation ranges from conventionally tilled to no-till. Conventional till operations typically consist of disking and harrowing followed by seeding with an air seeder or a mechanical drill and application of P and K fertilizer according to soil test. Nitrogen fertilizer or manures are usually not applied during the seeding year because this tends to stimulate weed growth more than growth of switchgrass. No-till planting usually involves treating existing vegetation with an herbicide and seeding with a no-till drill.

Studies on weed control for switchgrass[9] have shown that the herbicide atrazine often improves switchgrass establishment. An alternative method to chemical weed control is mowing the field to a height of 102 to 127 mm whenever the weeds reach 152 to 254 mm tall. Cassida *et al.*[10] investigated the use of several common herbicides singly or in combination with clipping. They found mowing to 200 mm provided additional weed control.

Annual maintenance

After establishment, switchgrass stands may be productive for 10 years or more. Nitrogen and water are the principal resources that limit switchgrass productivity.[11] Switchgrass shows little or no response to P and K.[12] However, P and K fertilizers and lime are recommended to maintain soil nutrient balance both during establishment and production years. In one study, yearly nitrogen application up to 150 kg ha^{-1} resulted in an average yield increase of 15 kg dry matter kg^{-1} N applied.[13] Vogel *et al.*[14] found optimum biomass yields of 10.6–11.2 Mg ha^{-1} at Mead, NE and 11.6–12.6 Mg ha^{-1} at Ames, IA when switchgrass was fertilized with 120 kg N ha^{-1}. Thomason *et al.*[15] evaluated the effects of N fertilizer application to switchgrass and found that a low to moderate amount of N (<112 kg N ha^{-1}) is sufficient for biomass feedstock production in South Dakota. Based upon a long-term study of N fertilizer application to switchgrass, approximately 50% less N appears sufficient to produce sustainable switchgrass than was originally reported.[2]

Harvesting strategies

Switchgrass growing season is from early spring (May–June) to late fall (October–November). The plant is harvestable at any time during the entire year depending upon the expected yield, quality, and final use.[17] Lemus *et al.*[16] reported 20 varieties of switchgrass in southern Iowa that had average yields ranging from 6.9 to 13.1 Mg ha^{-1}.

Frequency and time of harvest with respect to yield

An extensive body of research compares the yield and quality of switchgrass as a function of number of harvests and date of harvest. Thomason *et al.*[15] averaged switchgrass production data over three years and locations in Oklahoma test plots to estimate N application rate and number of cuts that would produce maximum yields. The highest annual yield was consistently achieved with 448 kg N ha^{-1} all applied in April and three harvests during the season averaging 18 Mg ha^{-1} of dry matter. Though multiple harvests produced more forage in the early years of their study, they observed a decline in switchgrass stands after 3–4 years of intensive harvest management. Madakadze *et al.*[18] studied the upland cultivars in short growing seasons in Canada and found that a single cut at the end of the season provided more biomass than did two or three cuts per growing season. Sanderson *et al.*[19] determined that in the long growing seasons in Texas, multiple harvests of the lowland variety, Alamo, reduced biomass yields over the four years of the study. Biomass yields were highest with a single harvest in mid-September. Parrish and Fike[20] concluded that for maximum biomass yield, a combination of low N inputs and a single harvest at the end of the season may be optimal for sustainable production of switchgrass as a biomass feedstock.

Switchgrass can be left in the field after maturity for harvesting the following spring. Jannasch *et al.*[21] reported a 30% reduction in biomass yield in Canada if this approach is taken. Similarly, Adler *et al.*[17] reported a 40% reduction in yield using a delayed harvest in Pennsylvania. In contrast, Parrish and Fike[20] reported that the biomass yield did not decline between a November harvest and a February harvest in Virginia.

Frequency of harvest with respect to quality

Translocation of nutrients, such as K, P, and N, and carbohydrates to the crown and root system as plants approach senescence is responsible for lower ash content of biomass at the end of the season. The reduction in ash content may also be attributed to increasing proportions of stem relative to leaf mass later in the growing season due to leaf loss during the winter. Delaying the harvest until spring could also increase the opportunity to leach minerals from the crop.[22,23] Adler *et al.*[17] found that delaying harvest to spring increased the energy content of biomass due to reduced moisture and ash content. The conversion efficiency of biomass to gases or to ethanol was dependent upon the conversion method and not on the time of harvest. The reduced ash content of material from a delayed spring harvest could potentially reduce the slagging and fouling of a combustion chamber. Adler *et al.*[17] concluded that the net energy yield per hectare decreases for spring harvest because of a lower yield of biomass. The reduction in yield and energy can potentially be alleviated by developing more efficient harvest equipment that would leave fewer residues on the field.

Moisture content

The moisture content of the plant decreases as the season progresses. In summer it can be more than 70%,[5, 24] decreasing to as low as 40% late in the fall. Sanderson *et al.*[19] reported changes in moisture content of switchgrass after the plant was mowed. The moisture content of cut switchgrass fell from 43% to 10–17% in 3 to 7 days, depending upon weather. Shinners *et al.*[24] noted that tedding (i.e., spreading) cut switchgrass in the swath almost doubled the drying rate in Wisconsin trials; moisture levels dropped from 46–66% to less than 20% (a level suitable for baling) in the afternoon of the third day of field drying. Sanderson *et al.*[19] reported mass fractions of a mature plant as 50% stem, 10–13% sheaf, 15–20% green leaves, and 10–12% inflorescence. These proportions were confirmed by Jannasch *et al.*[21]

Harvest options

Switchgrass harvest and post-harvest handling operations are similar to other grasses or crop residues.[25] Switchgrass in its southern range can grow to more than 3 m in height. The normal height of the plant ranges from 1.4 m in early summer to 1.8 m in late fall. The plant is well anchored to the ground by its deep root system and thus can be easily harvested by cutting devices.[26]

The trend in harvest and collection of biomass is to merge several operations within a single piece of equipment, so-called 'single-pass harvesting'. There is also a trend to make the resulting load (or package) as large as possible to reduce the number of trips to and from the field. Figure 1 shows two or more operations within a harvesting sequence contained within a box that can be achieved with a single piece of equipment. Moisture content of biomass is a key factor affecting the feasibility of merging field operations, and to the selection of either a dry system (e.g., baling) or wet system (e.g., chopping). Advanced options for harvest and collection will be discussed in the following sections.

Mowing and conditioning

Mowing can be integrated with conditioning in which the cut material passes through two or more rollers to crush or crimp the plant stem. A crimped stem takes half of the time for field drying relative to conventionally mowed forage.[27] Various degrees of crimping (sometimes called maceration or super conditioning) have been developed in recent years.[28] A mower-conditioner can be run at almost the same speed of a normal mower, about 6–8 km h^{-1}. The power requirement of the mower-conditioner can be twice that for a conventional mower (without conditioning rollers) depending on the degree of maceration.

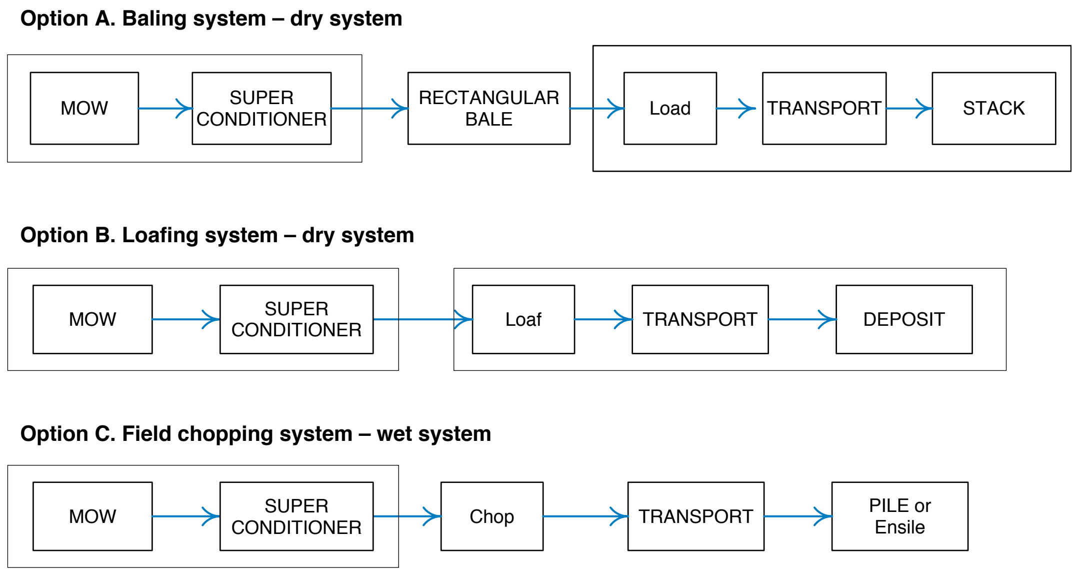

Figure 1. Advanced options for harvest and collection of switchgrass. The outer box (thin line) indicates that these operations can be assembled in a single piece of equipment.

Evaporation from a freshly cut windrow occurs primarily from the windrow surface. A rake gathers the swath off the ground into a narrower windrow. The wet part of the swath is exposed for uniform drying. For a fall harvest, a simple mower (without conditioner) may be adequate to cut the crop and place it in a swath. Shinners *et al.*[24] found that the drying rate of switchgrass in the swath was almost 35% faster than the drying rate for alfalfa.

Baling switchgrass

Bales can be either round or rectangular. Round bales (1.5 m wide by 1.8 m diameter) are popular on most US farms.[29,30] Limited experiences to date with switchgrass indicate that round bales may not be suitable for large-scale biomass handling. Round bales tend to deform under static loads in a stack, and misshaped bales are difficult to secure onto trucks to form a transportable load over open roads. Experience with switchgrass harvest at the Chariton Valley co-firing project in Iowa[31] showed that variation in the density of round bales was the cause of uneven size reduction and erratic machine operation during de-baling. Miles[32] specified large, rectangular bales 0.9 m x 1.2 m x 2.4 m (3'x 4'x 8') as the choice size for switchgrass. A larger rectangular bale of 1.2 m x 1.2 m x 2.4 m is also popular, but the density of these sized bales is about 10% less than the density of smaller bales. In contrast to round bales, square bales cannot shed rain and thus are prone to spoilage if not covered.

Large rectangular bales are made with tractor-pulled balers. Efforts are underway to design and develop self-propelled, large, rectangular balers. An automatic bale collector travels through the field, and collects and transports the bales to the side of the road where they are stacked. If an automatic bale collector is not available, bales are collected using a flatbed truck and a front-end bale grabber. The preference between an automatic bale collector and a flatbed truck depends upon the distance between the bale stacks and the farm. A flatbed truck may not be as efficient as automatic bale collection for forming stacks at the side of the farm. A loader is needed at the stack yard to unload the truck and stack the bales, whereas some automatic bale collectors stack the bales as they unload. While automatic bale handling is well-suited to large fields and relatively level land, it is not likely to be optimal in small fields or on steep slopes, as is the case in much of the south-eastern region of the United States.

Shinners *et al.*[24] tested the productivity of baling and bale storage for round bales of switchgrass in Wisconsin. Dry bales stored outdoors for 9 and 11 months averaged 3.4, 7.7, 8.3, and 14.9% dry matter loss for bales wrapped with plastic film, net wrap, plastic twine, and sisal twine respectively. Bales stored indoors averaged 3% dry matter

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loss. Preservation by ensiling bales in a tube of plastic film produced average dry matter losses of 1.1%. The density of bales (1.57 m wide by 1.60 m diameter) averaged 163 kg dry m^{-3}. Baler productivity ranged from 13.5 Mg h^{-1} for twine wrap to 17.7 Mg h^{-1} for net wrap. Twine wrap needed quadruple the wrapping time of net wrap.

Loafing

Another advanced option for collecting biomass is loafing. When biomass is dry (less than 15% m.c.) a loafer (or stacker) picks up the cut biomass from windrows and makes a large package of about 2.4 m wide, up to 6 m long and 3.6 m high.[33, 34] The roof of the loafer acts as a press, pushing the material down to increase biomass density to about 80 kg m^{-3}. This density gives a package roughly 4 Mg in mass. Once filled, the loafer transports the biomass to a storage area and unloads the stack. The top of the stack assumes the dome profile of the loafer roof and easily sheds water. Loafers were originally developed for on-farm livestock feeding of hay, but loaves proved to be awkward to reload and transport. Loafers were discontinued in the late 1970s when new, large balers became popular. As will be discussed below, large loaves may have merit as a low-cost biomass collection system.

Dry chop

Forage harvesting operation follows mowing once the grass is dried to less than 15% moisture content. The harvester picks up the biomass from windrows and chops it into smaller pieces (25–50 mm). The chopped material is blown into a forage wagon traveling alongside the forage harvester. Once filled, the self-propelled or towed wagon travels to the side of the farm where its contents are unloaded. A piler (inclined belt conveyor) is used to pile the material in the form of a large cone.

Wet chop

A forage harvester picks up the partially dry or wet biomass from the windrow. The chopped biomass is blown into a forage wagon that travels alongside the harvester. Once filled, the self-propelled or towed wagon travels to the side of the farm where the biomass is unloaded into either a bunker or a silage bag. The chopped material is often compacted to ferment and produce silage.[35]

Pre-processing and densification options

Loose cut switchgrass has a low bulk density ranging from 60 to 120 kg/m^3 depending on the particle size (Table 2). The bulk density of chopped and ground biomass can be increased substantially (~ 25%) by vibrating the biomass holder (e.g., truck box or container). To further increase density, the biomass must be mechanically compacted.[36] Densified biomass in the form of briquettes, cubes, and pellets results in bulk densities from 300 to 700 kg m^{-3}.[37]

Figure 2 shows a flow diagram for biomass densification options. Incoming biomass is either in chopped or bale form. Bales are cut into short pieces using a hydraulic piston pressing the hay against a grid of knives, or shredded using a roller-and-knife arrangement. Chopped biomass may require artificial drying if the moisture is more than 15%. (Drum dryers currently used for alfalfa can be used for drying switchgrass.) The shredded or chopped biomass is then ground in a hammer mill to an average size of 1 mm. The ground material will have a bulk density of approximately 180 kg/m^3 in the truck box. This density is suitable for short hauls less than 160 km. For longer hauls and long-term storage, it is preferred to increase the density of biomass further by pelletization. Assuming a production capacity of 6 Mg h^{-1} and an annual production of 45,000 Mg y^{-1}, Mani *et al.*[38] estimated the pelletization cost of saw mill residues to be \$10 to \$18 Mg^{-1} depending upon the size of a pelletization plant. Samson *et al.*[39] reported switchgrass pelletization cost at \$16.32 (the original CAD\$25.29 value is converted to 2000 US\$ at a conversion rate of 1.55). Sokhansanj and Turhollow[40] estimated the cubing costs for corn stover at roughly \$26 Mg^{-1}.

Table 2. Bulk density of switchgrass.

Form of biomass	Shape and size characteristics	Density (kg m^{-3})
Chopped biomass	20–40 mm long	60–80
Ground particles	1.5 mm loose fill	120
Baled biomass	Round or large squares	140–180
Ground particles	1.5 mm pack fill with tapping[1]	200
Briquettes	32 mm diameter x 25 mm thick	350
Cubes	33 mm x 33 mm cross section	400
Pellets	6.24 mm diameter	500–700

[1]Biomass is spread into the container while tapping the container

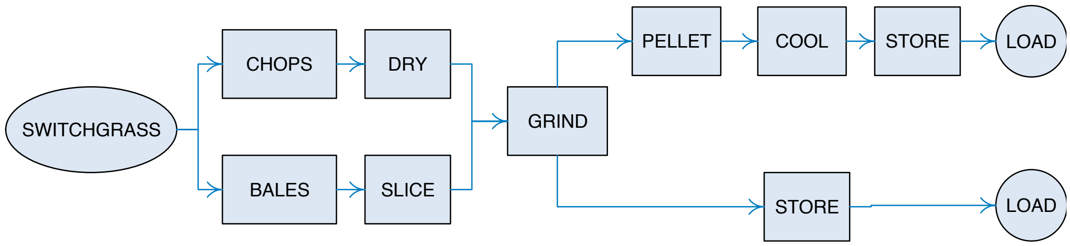

Figure 2. Flow diagram for densification of biomass to pellets or to small particles.

Mani *et al.*[38] also estimated an energy input of 956 MJ Mg^{-1} to produce pellets, if artificial drying can be eliminated from the production process. This is roughly 5% of the energy content in dry switchgrass (19.2 GJ Mg^{-1}). The most energy-intensive operation is the dryer (assumed drying from 40% to 10% dry mass wet basis), which requires about 2438 MJ Mg^{-1} of thermal energy. Jannasch *et al.*[41] found that electricity inputs of 62, 245, and 3271 MJ Mg^{-1} are required for coarse chopping, fine grinding, and pelleting of switchgrass (12% moisture), respectively. These values are slightly higher than those reported in Mani *et al.*[38]

Transport options

Physical form and quality of biomass have the greatest influence on the selection of equipment for the lowest delivered cost. In many instances, cost per unit distance is fixed for a given container size, independent of the mass to be transported. A higher bulk density will allow more mass of material per unit distance to be transported. Figure 3 depicts four potential transport options: truck, train, barge and pipeline. Truck transport is well developed and usually the cheapest mode of local transport, but it becomes expensive as travel distance increases. Transporting a slurry of chopped biomass and water through a pipeline is an attractive transport option with potentially favorable environmental features, but its feasibility and cost are less certain. One or a combination of several different transport methods with their unique loading and unloading challenges are involved. For example, transport via rail, barge or pipeline often requires integrated operation with truck transport.

The traditional way of estimating biomass transport cost is to consider a constant cost component and a variable cost component for the transport equipment. In case of rail and barge, a major component of fixed cost is the investment in the loading and unloading terminals as compared to the operating cost of loading and unloading. Typically, the variable cost component is reported in '$ per km per Mg'. This component of transport cost accounts for fuel, depreciation, maintenance and labor. Table 3 summarizes the basic fixed and variable cost components for estimating the cost of transporting biomass via truck, rail, barge, and pipeline.

Biomass is first trucked to the pipeline inlet terminal. Biomass is then slurried at the inlet terminal and transported by pipeline. Table 3 only includes the transportation

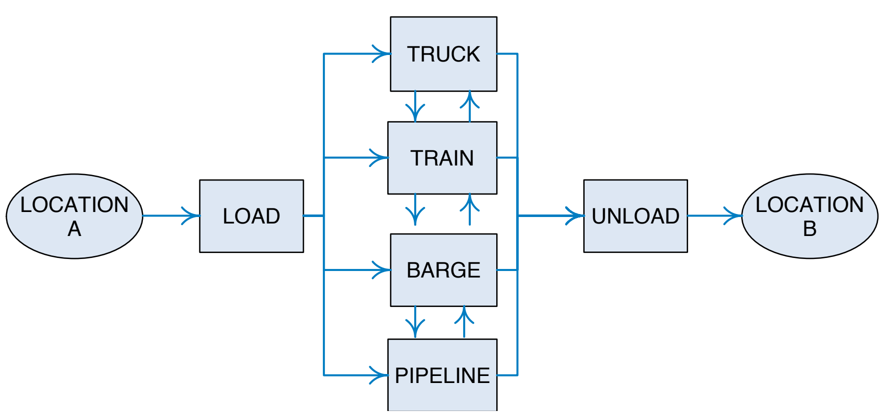

Figure 3. Transporting biomass from location A to location B.

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cost by pipeline and not the preliminary trucking costs. Truck transportation cost to the pipeline inlet will depend on the size of the biorefinery and the mass of each truckload. Hence truck transportation cost should be added to the pipeline transport cost wherever this is applied. Pipeline transportation cost in Table 3 is for pipeline transporting 1 million dry Mg of biomass per year at a concentration of 30% solids. Since there are no data available on the friction loss of switchgrass slurry, friction loss for a woodchip slurry is used here to calculate the pump power. Details on pipeline transport of biomass can be found in Kumar *et al.*[42–44] A similar approach of integration of truck with rail is required when using rail to transport biomass. Details on rail transport of biomass can be found in Mahmudi and Flynn.[45]

Figure 4 compares the cost of transporting biomass using four modes of transport. In this model, the transport cost for truck and rail does not change with capacity (in real situations the sizes of contracts with transport companies affects these fixed prices). For rail, barge and pipeline, an integrated operation is assumed that accounts for initial trucking costs, including loading and unloading. Truck transport is the least expensive option for distances less than 160 km. Above 160 km, rail is cheapest. Pipeline transport cost can be reduced significantly by increasing the size of pipeline and concentration of slurry. The fixed cost of shipping on waterways is high while the distance variable cost is low at about \$0.01 Mg^{-1} km^{-1}. The road and waterway transport costs intersect at about 270 km. The cost structures for rail, barge and pipeline transport are much more complex

Table 3. Cost and energy consumption equations for transporting biomass using truck, rail, and pipeline.

Transport mode	Cost (\$ Mg^{-1})	Energy consumption (MJ Mg^{-1})
Truck[1]	5.70+0.1367 X	1.3 X
Rail[2]	17.10+0.0277 X	0.68 X
Barge[3]	34.01+0.01 X	–
Pipeline[1,4]	$2.67Q^{-0.87}+0.137XQ^{-0.44}$	$160.2Q^{-0.87}+22.2\ XQ^{-0.44}$

[1] Kumar *et al.*[42]
[2] Mahmudi and Flynn.[45]
[3] Searcy *et al.*[46]
[4] X is distance traveled (km); Q is the weight of biomass transported (Mg).

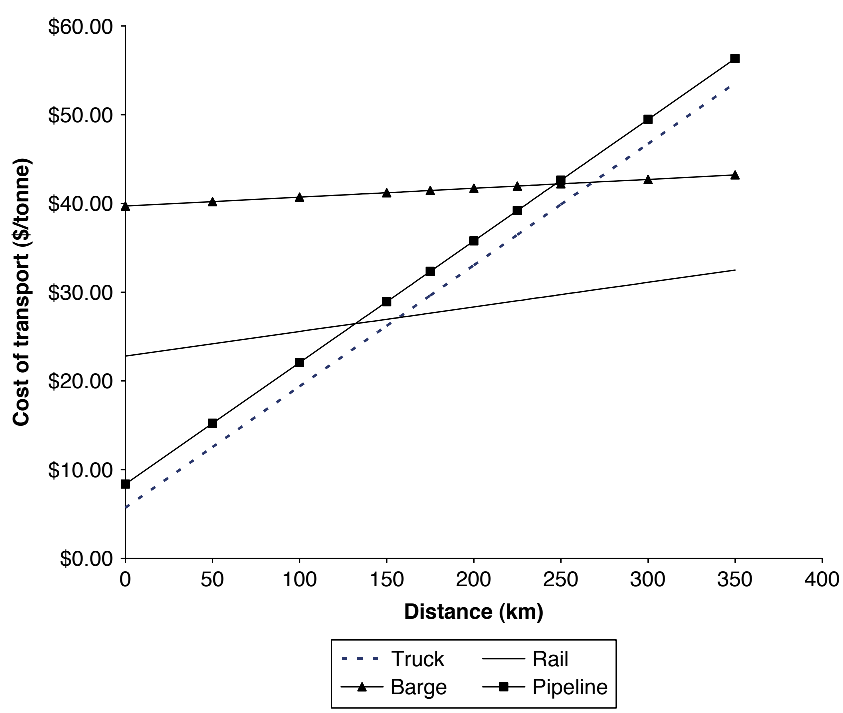

Figure 4. Transport cost of switchgrass using four modes of transport. For pipeline an annual capacity of 1 million Mg is assumed.

than the simple linear equation presented in this work. For example, the average rate of barge transport of grain from St Paul, MN to New Orleans, LA is quoted at \$6.81 Mg^{-1} and from St Louis, MO to New Orleans, LA at \$4.39 Mg^{-1}.[46] In cases where multiple modes of transport are required, the cost structure will be a blend of two or three of these modes.

Table 3 lists estimates for energy consumption by truck, rail, and pipeline. The energy consumption for truck and for rail is 1.3 and 0.68 MJ Mg^{-1} km^{-1}, respectively.[42,47] It is assumed that diesel fuel is used for both truck and rail. The electrical power for pumping is produced from a coal-fired power plant, with an assumed electricity price of \$0.06 kWh^{-1} to convert from the cost (\$) to energy (MJ) consumption for the pipeline.

Costs and energy inputs

Cost and energy input for producing switchgrass

The cost of producing switchgrass includes three major components: i) establishment; ii), reseeding; and iii) annual management. The production cost data in Table 4 are extracted from Duffy and Nanhou.[48] The energy input for switchgrass production is limited to crop establishment, reseeding, and annual maintenance. The components of energy input for the production of switchgrass includes energy content of diesel fuel[50, 51], energy required to produce and transport fertilizers and herbicides, and energy required to produce seed for planting.[49] Energy required to produce switchgrass seed was assumed to be the same as that for ryegrass.

Table 4 shows that the cost of producing switchgrass is \$53.61 Mg^{-1} in the first year, and \$8.95 Mg^{-1} in the second year with 25% probability of reseeding. After establishment, an annual maintenance cost of \$35.70 Mg^{-1} is required. We estimate that switchgrass production requires an energy input of 721 MJ Mg^{-1}, not including harvesting. Kim and Dale[49] conducted a cumulative energy analysis of switchgrass production and found that about 970 to 1340 MJ of energy was required to produce 1 Mg of switchgrass. The higher energy input values were due to the use of high energy conversion factors used for fertilizer production.[49]

Production costs and energy input per unit mass of switchgrass produced are reduced when the biomass yield increases from the current base production of 10 Mg ha^{-1}. The recommended seeding rate is 4–10 kg ha^{-1},[20] depending upon the emergence of the plants which in turn depends upon the concentration of dormant seeds in a lot. The dormancy

Table 4. Costs and energy input for switchgrass establishment and annual production on cropland for a base case of 10 Mg ha^{-1}

Operations	Establishment[1] (\$ ha^{-1})	Reseeding[2] (\$ ha^{-1})	Maintenance[3] (\$ ha^{-1})	Energy Input[4] (MJ ha^{-1})
Machinery (land preparation)	66.32	29.76	30.88	182
Seed	69.86	46.57	0	20
Fertilizer (soil amendment)[5]	154.99	50.08	94.51	5007
Chemicals (herbicides and insecticides)	19.93	19.93	19.93	1998
Land charges	224.96	211.78	211.69	–
Total (\$ ha^{-1})	536.05	89.53	357.01	7207
\$ Mg^{-1} (levelized cost for a yield of roughly 10 Mg ha^{-1})	53.61	–	35.70	721[6]
% of feedstock HHV[7]	–	–		3.76

[1]First year.

[2]Second year with 25% probability of reseeding.

[3]production years.

[4]For maintenance year.

[5]Including lime application.

[6]MJ Mg^{-1}.

[7]The high heat value (HHV) of dry switchgrass is roughly 19.2 GJ Mg^{-1}.[58]

of fresh switchgrass seed is 5–10%. A planting density of 10–20 m^{-2} is acceptable[20] for establishing a healthy plant. Muir *et al.*[3] obtained a yield of 15 Mg ha^{-1} in Texas with a fertilizer application rate of 128 kg N ha^{-1}. They achieved a maximum switchgrass yield of 22 Mg ha^{-1} when 168 kg of N ha^{-1} was added and the growing season rainfall exceeded 676 mm in Stephenville, TX. We used the 160 kg N ha^{-1} application rate when projecting production costs for future yield increases of up to 30 Mg ha^{-1}. We also assumed the cost of establishment and reseeding remains constant. The cost does not increase with increasing switchgrass yield. Development of hybrid varieties (high-biomass-yielding switchgrass) may slightly increase the cost of seeding. Figure 5 plots the data of Duffy and Nanhou[48] where they calculated the incremental cost of producing switchgrass in Iowa. The original data included roughly \$400 ha^{-1} for harvest cost. We deducted this cost (\$400) from their total production and harvest cost to generate the curve in Fig. 5 that shows the pre-harvest production cost decreasing exponentially with the increased yield. The \$32 Mg^{-1} pre-harvest production cost at 10 Mg ha^{-1} drops by almost half to \$18 Mg^{-1} at 20 Mg ha^{-1} and to \$12 Mg^{-1} at 30 Mg ha^{-1}. This pattern is consistent with that reported by Bransby *et al.*[63]

Table 5 summarizes the biomass cost and energy input for the projected increases in biomass yield. For the analyses, all of the base case cost and energy inputs were kept constant except nitrogen application rates. The data do not include reduction in the cost of machinery per unit production. This may help explain why the costs recorded in Table 5 are higher than those plotted in Fig. 5.

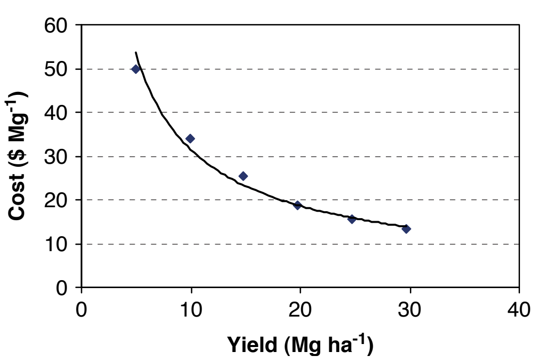

Figure 5. Effect of yield on the cost of pre-harvest switchgrass production (extracted from Duffy and Nanhou).[48]

Table 5. Switchgrass production cost and energy input at various biomass yield in the cropland.

Biomass yield (Mg ha^{-1})	Cost1 (\$ Mg^{-1})	Energy input (MJ Mg^{-1})	% of HHV[2]
10	41.50	721	3.76
15	30.71	692	3.60
20	24.92	650	3.39
30	19.14	607	3.16

[1]Switchgrass production cost is reported in 2006 US\$.

[2]The high heat value (HHV) of dry switchgrass is roughly 19.2 GJ Mg^{-1}.[58]

Cost and energy input for harvesting switchgrass

The Integrated Biomass Supply Analysis and Logistics (IBSAL) model[52,53] was used to calculate cost and energy inputs for the four collection options outlined earlier. The hourly costs in the model were calculated using the procedure and data described by Sokhansanj.[52] The weather data consisted of average daily dry bulb temperature, relative humidity, rainfall, snowfall, and evaporation obtained from TMY (Typical Meteorological Year) for Idaho Falls, Idaho, USA. The base data for machinery performance were those for harvesting a forage crop at a yield (crop density) of 5.6 dry Mg ha^{-1}. To handle the increased yield, we assumed the working capacity of a machine increases to cover the same field area per unit time (ha h^{-1}). A power factor of 0.6 was used to calculate the cost and power of the equipment for handling increased yield (crop density),

$$C_{new} = C_{base}\left(\frac{Y_{new}}{Y_{base}}\right)^{0.6} \tag{1}$$

where Y is the yield and C is the cost (or power input). We used 5.6 dry Mg ha^{-1} for Y_{base}. C_{base} is base cost (or power) used in IBSAL.[52–54]

Figures 6 and 7 show that as yield increases the cost and energy input per unit mass of biomass harvested decreases exponentially. Loafing is the least-expensive scenario for switchgrass harvest; dry chop is the most expensive. Baling operating is the current technology for handling dry forage. The operation is more expensive than loafing but baling is cheaper than silaging (wet chop system). Trends for energy input correlate with cost. Loafing consumes the least energy followed by baling.

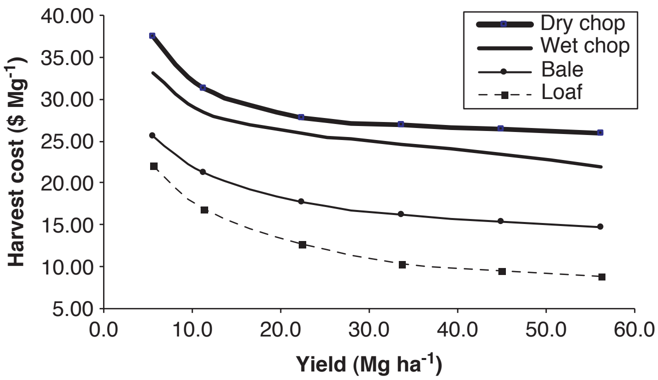

Figure 6. The unit cost of four harvest scenarios as a function of yield (crop density).

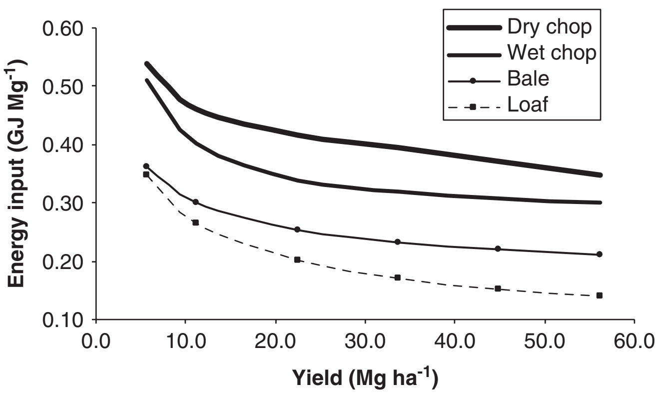

Figure 7. The unit energy input for four harvest scenarios as a function of yield (crop density).

Cost and energy input for transporting switchgrass

Unlike harvesting where costs are relatively independent of scale, biorefinery size does affect the cost of transport where a biomass supply area surrounds the biorefinery. Increased tonnage increases the radius of supply area and thus the transport distance. Figure 8 indicates the relationship between maximum transport distance and net yield for a 2000 Mg d^{-1} and 5000 Mg d^{-1} biorefinery. We assumed 25% of the cultivated area surrounding the biorefinery is allocated to switchgrass. The maximum distance for a yield of 10 Mg ha^{-1} is roughly 27 km for a 2000 Mg d^{-1} plant and 43 km for a 5000 Mg d^{-1} plant. The distance decreases to 19 km and 30 km, respectively when the yield increases to 20 Mg ha^{-1}.

Transport costs depend on biomass form (i.e., bulk density and the size of transporter). We used IBSAL to calculate the cost of transport for three forms of biomass: bale, loose

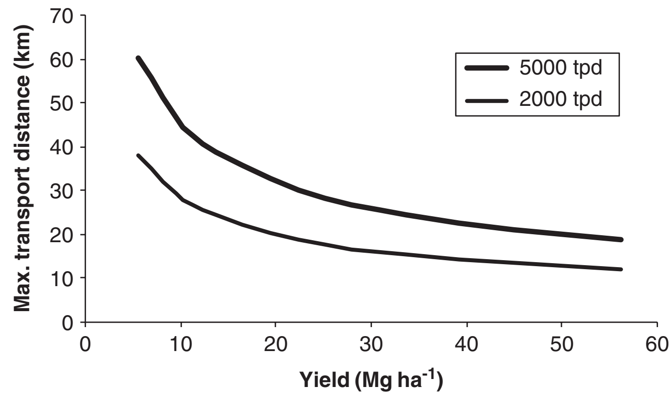

Figure 8. Maximum transport distance as a function of yield for two biorefinery capacities. 25% of a circle around the plant is cultivated to switchgrass.

chop, and pellets. The transport of wet chops from silage will be evaluated in future publications. Table 6 shows the cost and energy input for pelletizing switchgrass with an annual production of 45,000 Mg. A pellet production cost of \$10 Mg^{-1} can be achieved if the pellet production rate is increased to 18 Mg h^{-1}.

For bale transport, the biomass is loaded onto a flatbed truck trailer. The bales are unloaded, stacked, and ground at the biorefinery. When transporting ground material, the bales are ground at the stack yard next to the farm, loaded into a truck box (similar to a grain truck), and transported to the biorefinery where the content of the truck box is dumped. For pellet transport, the pellets are loaded into the

Table 6. Cost and energy input for pelleting switchgrass

Operations	Cost ($ Mg^{-1})	Energy input (MJ Mg^{-1})
land cost	0.28	0
Feeding system	3.52	99
Grinding	1.60	267
Pelleting	3.63	391
Pellet cooling	0.47	64
Screening	0.17	69
Storage	0.08	0
Labor	7.61	0
Miscellaneous	0.61	66
Total cost	17.97	956
% of HHV		4.98

truck box and transported to the biorefinery. All grindings are done to a particle size of 6 mm. We assumed that pellets are fed directly to the biorefinery.

Table 7 lists the costs and energy inputs associated with processing, loading, transporting, and unloading. Results indicate that the costs and energy input generally increase when the capacity of a biorefinery increases from 2000 to 5000 Mg d^{-1}. This is due to the increased travel distance (Fig. 8). The increased yield from 10 to 30 Mg ha^{-1} results in a slight reduction in transportation costs and energy input due to larger volumes of biomass being available closer to the biorefinery. The format of biomass (bales, ground, or pellets) has the largest influence on the transport cost and energy input. Baled biomass has a bulk density of about 160 kg m^{-3}. Ground biomass with a particle size of less than 6 mm also has a bulk density of 160 kg m^{-3}. The lower cost of transporting ground biomass compared to that of baled biomass is due to bulk handling of ground biomass. Pelletized biomass has the lowest transport cost because of the high bulk density and bulk handling properties. In these calculations, we did not impose any weight restrictions on the transporter. Typical gross weight limit for trailer trucks operating in the State of Idaho is 47.72 Mg.[58]

Summary of costs and energy inputs

In this section we summarize the costs and energy inputs (as a percentage of higher heat value of dry switchgrass 19.2 GJ Mg^{-1}) for producing, harvesting, and transporting switchgrass. The summations are presented numerically in Table 8 and in bar graph format in Fig. 9. Table 8 compares the delivered cost of biomass at a yield of 10 Mg^{-1} using the current baling technology and future granulation (pelletization) technology. We expect not much change in crop production practices when the yield remains the same, so the cost of production remains at \$41.50 Mg^{-1}. A system similar to loafing by which the biomass is collected as a large package in a single step will result in cost reductions from \$23.72 to \$17.50 Mg^{-1}. Savings will also be realized in bulk handling of pelletized material where the cost of transport will be reduced from \$15.42 to \$12.16 Mg^{-1}. The overall cost reductions from the current baling and bale transport to future loafers and pelletized biomass will be from \$80.64 to \$71.64 Mg^{-1}, roughly 12%. Reductions in energy input will be slightly less than 8%.

Figure 9 shows the total delivered costs and energy input for the above mature technology scenario, i.e., loafing, pelletizing, and truck transport without load limitations at biomass yields of 10, 20, and 30 Mg ha^{-1}. The assumed biorefinery scale was 5000 Mg d^{-1}. The delivered cost at the mature technology phase decreases from \$70 Mg^{-1} to almost \$49 Mg^{-1}, a drop of almost 30% for a biomass yield increase from 10 to 20 Mg ha^{-1}. The delivered cost decreases further by more than 18% to \$40 Mg^{-1} when the yield increased to 30 Mg ha^{-1}. The corresponding reductions in energy input were 6% and 10% for 20 and 30 Mg ha^{-1}.

Comparing the delivered cost and energy input for two plant capacities of 2000 and 5000 Mg d^{-1} for mature technology showed a slight increase in the delivered cost from

Table 7. Cost and energy input for transporting three biomass formats from farm to biorefinery. Calculations are made for two biorefinery capacity (2000 Mg d^{-1} and 5000 Mg d^{-1}) and for three yields of 10, 20, and 30 Mg ha^{-1}.

		Cost (\$ Mg^{-1})			Energy input (GJ Mg^{-1})		
Biorefinery capacity	Format	10 Mg ha^{-1}	20 Mg ha^{-1}	30 Mg ha^{-1}	10 Mg ha^{-1}	20 Mg ha^{-1}	30 Mg ha^{-1}
2000 Mg d^{-1}	Bale	15.83	15.28	15.10	0.407	0.381	0.374
	Ground	14.42	13.53	13.16	0.284	0.249	0.234
	Pellets	11.67	11.48	11.37	0.479	0.471	0.468
5000 Mg d^{-1}	Bale	16.39	15.55	15.13	0.516	0.476	0.455
	Ground	16.07	14.78	14.23	0.349	0.299	0.277
	Pellets	12.16	11.79	11.65	0.498	0.484	0.479
% of HHV	–	–	–	–	2.59	2.52	2.49

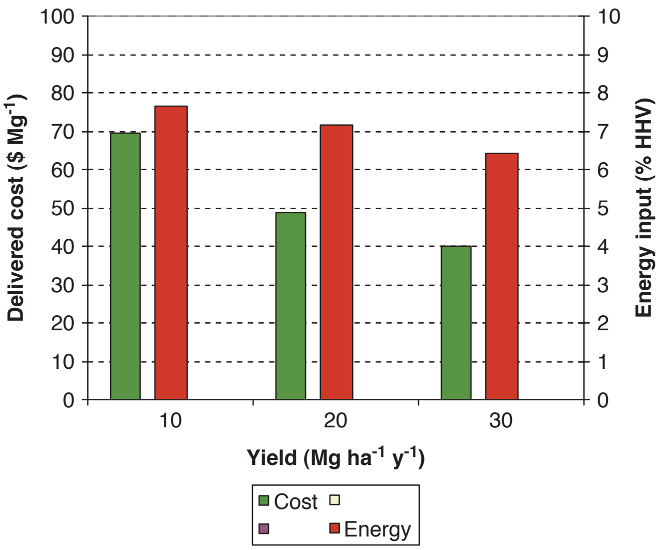

Figure 9. Delivered cost and energy input for mature technology supply chain vs biomass yield (5000 Mg d^{-1}).

an increase in biomass tonnage. The increase was due to an increase in maximum transport distance from 20 km to 30 km (Fig. 8). The percent increase in energy was slightly higher than the percent increase in cost but increases in overall delivered cost and total energy input were insignificant.

Growth in biomass collection and supply equipment

The growth of switchgrass production and yield requires new infrastructure in equipment and storage facilities. We can estimate the size and value of these infrastructures using current data on machinery costs, performance, and power requirements. Using cost data and equipment allocation previously published,[55] we calculated the total cost (or value) of equipment and buildings necessary to process the biomass quantities in 2015 and 2030.

Figure 10 summarizes the value of equipment where the operations are grouped into five categories of production, collection, transport, storage, and power consumption.[56] We assumed a larger proportion of biomass will be either chopped for wet silage or, if it is dry, packed in a large package similar to a loaf. The value of equipment used in production was estimated at more than $600 million for 30 Tg in 2015 and more than $2.1 billion for 100 Tg in 2030. Similar increases are expected for collection, transport equipment and storage buildings. The value of tractor power increases from $200 million in 2015 to more than $600 million in 2030. The total value of production and supply of switchgrass will be roughly $2.76 billion in 2015 and $8.25 billion in 2030.

It takes time to attain the projected increases in acreage and tonnage of switchgrass. To put this in perspective, it would take 6–7 years to get a full production from a switchgrass project. This starts from Year 1 for cultivar selection, Year 2 for setting up farmer contracts, Year 3 for spring planting. It takes then three more years until the crop is established to its full maturity. This number of years does not account for challenges in reallocation of land to supply feedstock to bioenergy. Sanderson and Adler[61] and Samson *et al.*[62] discuss the potential conflicts between the growth of perennial crops for bioenergy and the traditional forages that support livestock industry in the USA.

Table 8. Summary of cost and energy inputs to produce and deliver switchgrass using current and mature technology (yield 10 Mg ha^{-1}).

	Current (Yield 10 Mg ha^{-1})			Mature (Yield 10 Mg ha^{-1})		
Step	Technology	Cost ($ Mg^{-1})	Energy (GJ Mg^{-1})	Technology	Cost ($ Mg^{-1})	Energy (GJ Mg^{-1})
Planting & cultivation	Current	41.50	0.721	Fertilization & crop management	41.50	0.721
Harvest & storage	Baling system	23.72	0.340	Loaf (single pass)	17.50	0.275
Transport	Bales	15.42	0.407	Pelletized	12.16	0.498
Total	–	80.64	1.638	–	71.16	1.494
% of HHV1	–	–	8.5	–	–	7.8

[1]The high heat value (HHV) of dry switchgrass is reported at roughly 19.2 GJ Mg^{-1}.[58]

  | *Biofuels, Bioprod. Bioref.* **3**:124–141 (2009); DOI: 10.1002/bbb

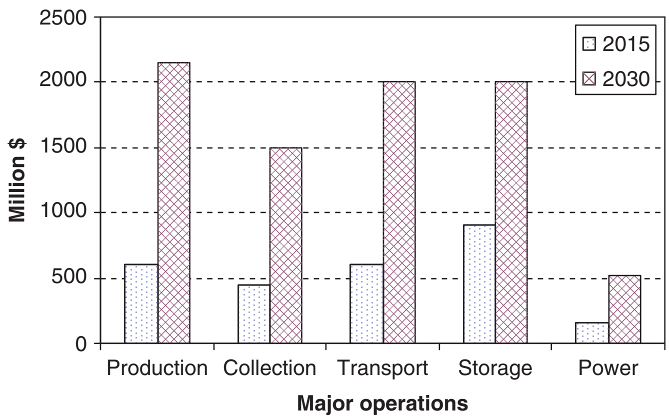

Figure 10. Projected value of equipment for 30 million Mg and 100 Mg switchgrass production and handling in 2015 and 2030, respectively.

Discussion

Although switchgrass is relatively difficult to establish, selecting appropriate cultivars and best management practices for a particular region would lead to successful long-term production. Switchgrass varieties Alamo, Kanlow, and Cave-In-Rock are the most widely used cultivars in the south-east and mid-west regions. Published literature indicates that switchgrass yield can be maximized with optimal N application and harvesting strategies. Yields can likely be improved further through plant breeding and genetic techniques. A single-cut harvesting of switchgrass at the end of the season provides an optimal biomass yield for sustainable production of biomass feedstock. It is possible to achieve yields of 20 dry Mg ha^{-1} but such yields may drop by half if harvest is delayed to the next spring. The reduction in harvestable biomass is due to physical deterioration of the crop in the field over winter due to rain, wind, and snow. The 'yield' we use in this paper represents the amount collected from the field. It does not represent the total amount of the above-ground biomass. The values we present in this paper are projected assuming high yields.

Except for baling, other collection methods such as loafing and wet or dry chopping have not yet been tested for switchgrass. The authors' experience with handling agricultural fibrous material indicates that the most practical method of handling switchgrass will be to densify and granulate (pelletize) the material as soon as it is harvested, provided a limit on moisture content for safe storage (generally less than 20%) is observed. Baling, transporting bales, and grinding bales at the biorefinery site are expensive and energy-consuming options. Loafing, grinding, and transporting grind from field to biorefinery using trucks is the cheapest sequence and least energy-intensive option. Pelletization costs and energy requirements are reduced if artificial biomass drying, which adds \$10 Mg^{-1}, can be eliminated. The process could also be optimized with respect to applied pressures, particle size, and moisture contents.[57] Experiments indicate that treatment of ground alfalfa with high temperature (>90°C) resulted in durable pellets. Developing low-cost binders will also help in producing durable pellets.[37] The current cost of pelletization of biomass based on using equipment similar to pelletizing sawdust and animal feed is high.

From limited experience in Europe[55] in harvesting fibrous crops that yield up to 20 Mg ha^{-1} (hemp, kenaf, giant reed, miscanthus), the crop is generally cut and swathed in the field using high-powered rotary cutters. The cut plants are left in a swath to field-dry followed by baling using round or square balers. There are no extensive field data to validate the performance of equipment dealing with different yields. Our calculations show that making packages as large as possible (loaves) reduces costs. Huisman[58] states that in cases where the high yielding green biomass (e.g., hemp) is chopped and baled, the baling density has reached 250 kg m^{-3}. It is not clear from the publication whether this high density is for dry or green biomass.

North America has seen a tremendous increase in the power of tractors used in agriculture over the past 50 years. Kim *et al.*[59] analyzed using data from 926 diesel tractors tested at the Nebraska Tractor Test Laboratory from 1959 through 2002. They found that the average specific volumetric fuel consumptions for the maximum PTO (power take off) increased by 21% to 3.47 kWh/L while the average maximum PTO power per unit mass of a tractor increased by 72%. Tractors with a greater PTO power than 187 kW had an average torque rise of 51%, which was a 31% increase over the same period. The general consensus is, however, that there will not be any more rises in the power of tractors but tractors will continue to have a greater power-to-mass ratio, which results in the tractors traveling faster.[60] Another reason for limiting the increase in size of future tractors is increasing soil compaction that affects soil conservation as well as plant growth. We foresee, however, that growing, harvesting, and handling switchgrass will generate new income to the equipment-manufacturing industry.

The delivered cost of biomass is a function of the scale of biomass production. The cost is made up of three components[61]: (i) a fixed value that is the sum of the biomass production, biomass harvest, and other costs that do not vary with the size of conversion facility; (ii) a variable feedstock transport cost that is proportional to the size of the conversion plant (biofuel production) to the 1.5 power; and (iii) the variable biofuel conversion costs that is proportional to the plant size to a 0.6 or 0.7 power. The components of the cost equation indicate that the unit cost of biomass feedstock is a strong function of the transport costs, increasing with the size of the plant. In other words, the scale factor (bigger is cheaper) – which is an important consideration in sizing the conversion facility – may not hold for facilities that are dependent upon biomass supply from the vicinity.

In this paper, we presented cost figures for operations that are involved in production, harvest, storage, and transport of biomass. The calculated overall delivered costs include all customary inputs including labor and management. The costs do not include a net profit or a net return on investment for biomass producer or biomass handler. Most of the costs are in 2006/2007 dollars when the manuscript was in preparation. In projecting costs in future, we did not include probable increases in cost of fuels and services and general expected inflation. Nevertheless, the numbers indicate the potential costs and the economic implications of production and supply of biomass switchgrass.

Conclusions

1. An increased yield from 10 Mg ha^{-1} to 30 Mg ha^{-1} reduced the cost of switchgrass production from \$41.50 Mg^{-1} to \$19.14 Mg^{-1}, although this relationship is not linear.
2. A loafing system which in effect eliminates the need for two-pass baling and bale transport was the least expensive operation evaluated in this study, especially for high yielding switchgrass. The cost of harvest using baling was \$23.72 Mg^{-1} for a yield of 10 Mg ha^{-1} and was reduced to \$9.59 Mg^{-1} for a yield of 30 Mg ha^{-1}. The loafing cost for 10 Mg ha^{-1} was \$17.50 Mg^{-1}.
3. The cost of truck transport ranged from \$15.42 Mg^{-1} for baled biomass and a yield of 10 Mg ha^{-1} to \$11.65 Mg^{-1} for granulated (pelletized) biomass at a yield of 30 Mg ha^{-1}. The increased bulk density of biomass as a result of granulation was also responsible for the cost reduction.
4. The total cost of delivered switchgrass was \$80.64 Mg^{-1} for 10 Mg ha^{-1} and \$39.33 Mg^{-1} for 30 Mg ha^{-1}. The total energy input was reduced from 1.638 GJ Mg^{-1} to 1.202 GJ Mg^{-1}. This equivalent to 8.5% and 6.2% of the high heat value of switchgrass at 19.2 GJ Mg^{-1}.
5. We estimated that the total direct economics activity (fixed cost and operating costs) in production and supply of switchgrass may reach \$2.76 billion in 2015 and \$8.25 billion in 2030.

Acknowledgements

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Conversions

From	to	Multiply by
kg m^{-3}	lb/ft^3	0.063
kJ kg^{-1}	Btu/lb	0.429
Mg ha^{-1}	ton/ac	0.447
MJ Mg^{-1}	MBtu/ton	0.858
MJ Mg^{-1} km^{-1}	Btu/ton-mile	138.288
\$ Mg^{-1}	\$/ton	0.906

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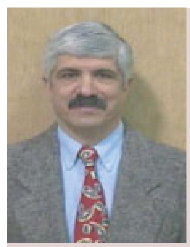

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