Net energy of cellulosic ethanol from switchgrass

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Perennial herbaceous plants such as switchgrass (*Panicum virgatum* L.) are being evaluated as cellulosic bioenergy crops. Two major concerns have been the net energy efficiency and economic feasibility of switchgrass and similar crops. All previous energy analyses have been based on data from research plots (<5 m^2) and estimated inputs. We managed switchgrass as a biomass energy crop in field trials of 3–9 ha (1 ha = 10,000 m^2) on marginal cropland on 10 farms across a wide precipitation and temperature gradient in the midcontinental U.S. to determine net energy and economic costs based on known farm inputs and harvested yields. In this report, we summarize the agricultural energy input costs, biomass yield, estimated ethanol output, greenhouse gas emissions, and net energy results. Annual biomass yields of established fields averaged 5.2 -11.1 Mg·ha^{-1} with a resulting average estimated net energy yield (NEY) of 60 GJ·ha^{-1}·y^{-1}. Switchgrass produced 540% more renewable than nonrenewable energy consumed. Switchgrass monocultures managed for high yield produced 93% more biomass yield and an equivalent estimated NEY than previous estimates from human-made prairies that received low agricultural inputs. Estimated average greenhouse gas (GHG) emissions from cellulosic ethanol derived from switchgrass were 94% lower than estimated GHG from gasoline. This is a baseline study that represents the genetic material and agronomic technology available for switchgrass production in 2000 and 2001, when the fields were planted. Improved genetics and agronomics may further enhance energy sustainability and biofuel yield of switchgrass.

agriculture | bioenergy | biomass | biomass energy | greenhouse gas

A renewable biofuel economy is projected as a pathway to reduce reliance on fossil fuels, reduce greenhouse gas (GHG) emissions, and enhance rural economies (1). Ethanol is the most common biofuel in the U.S. and is projected to increase in the short term because of the voluntary elimination of methyl tertiary butyl ether in conventional gasoline and in the long term because of U.S. government mandates (2, 3). Maize or corn (*Zea mays*) grain and other cereals such as sorghum (*Sorghum bicolor*) are the primary feedstock for U.S. ethanol production, but competing feed and food demands on grain supplies and prices will eventually limit expansion of grain-ethanol capacity. An additional feedstock source for producing ethanol is the lignocellulosic components of plant biomass, from which ethanol can be produced via saccrification and fermentation (4). Dedicated perennial energy crops such as switchgrass, crop residues, and forestry biomass are major cellulosic ethanol sources that could potentially displace 30% of our current petroleum consumption (5).

Net energy production has been used to evaluate the energy efficiency of ethanol derived from both grain and cellulosic biomass (6). Typically, studies have used net energy values (NEV), net energy ratios, and net energy yield (NEY) and have compared biofuel output to petroleum requirements [petroleum energy ratio (PER)] to measure the sustainability of a biofuel. In initial analyses, switchgrass was estimated to have a net energy balance of 343% when used to produce biomass ethanol (7). More recent energy model analyses that used simulated biomass yields and estimated agricultural inputs indicate that switchgrass could produce $>$700% more output than input energy (8–10), whereas GHG have been assumed to be near zero (1) or estimated to be slightly positive (8) for ethanol derived from switchgrass.

Lignocellulosic feedstocks such as switchgrass, woody plants, and mixtures of prairie grasses and forbs have been proposed to offer energy and environmental and economic advantages over current biofuel sources, because these feedstocks from perennial plants require fewer agricultural inputs than annual crops and can be grown on agriculturally marginal lands (11). An estimated 3.1×10^6 to 21.3×10^6 ha (1 ha = 10,000 m^2) of existing agricultural land in the U.S. is projected to be converted to perennial grasses for bioenergy based on theoretical market prices (1). The majority of land for perennial grass production is projected to come from the reallocation of existing cropland, with land currently enrolled in the Conservation Reserve Program (CRP) and pastures being second and third, respectively. The CRP was authorized by the Food Security Act of 1985 and had a goal of removing highly erodible marginal cropland from crop production by paying farmers and land owners to revegetate the land with perennial grasses and trees. The cropland base predicted to be converted to perennial grass biomass systems will be similar to existing CRP land (12).

Unlike corn, for which long-term data on grain yield and agricultural inputs in the U.S. are available, data for switchgrass and other perennial herbaceous plants grown and managed as bioenergy crops are limited and are based largely on small-plot research, in which plots are typically <5 m^2. To obtain relevant field-scale information for switchgrass managed as a biomass energy crop, we conducted trials using fields on 10 farms in the midcontinental U.S. (Fig. 1) for 5 yr to obtain production information for use in net energy and economics analysis. Adapted switchgrass cultivars were grown and managed as a biomass energy crop in fields on four farms each in Nebraska and South Dakota and two farms in North Dakota using management practices developed in previous small plot research.

Cooperating farmers, who were paid for their work and land use, documented all production operations and field biomass yields. This study provided 5 yr of production and management information from each farm, which we used to estimate net energy, petroleum inputs to ethanol outputs, and GHG emissions.

Results

Agricultural Inputs. Total agricultural inputs were less during the establishment year than in postplanting years, because nitrogen fertilizer, a major agricultural energy input (9), was not applied per recommended management practices (Fig. 2). In the establishment year (Fig. 2), herbicides (33%), diesel fuel (29%), and seed (23%) were the top agricultural energy inputs. Nitrogen

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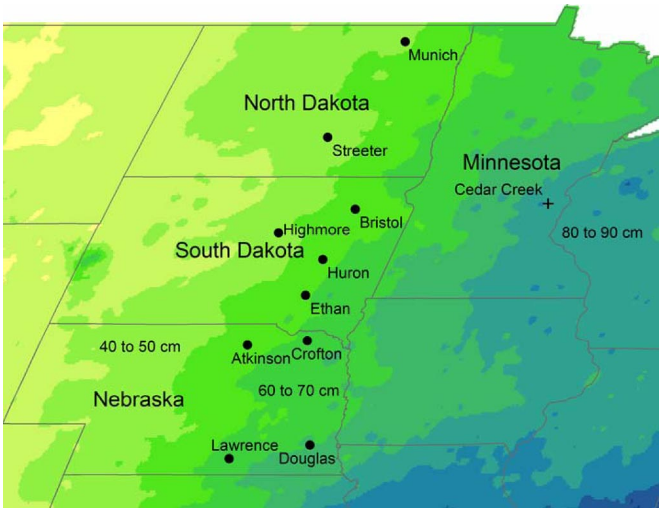

Fig. 1. Switchgrass field locations managed for bioenergy (filled circle) and human-made prairie plots (+) with average annual precipitation zones for 2000–2005 (13).

fertilizer (67%), diesel fuel (18%), and herbicides (8%) accounted for the majority of agricultural energy inputs (Fig. 2) for postplanting harvest years. Nitrogen fertilizer requirements varied by location, because of estimated potential yields based on stand density, regional precipitation and soil moisture information, and cooperator judgment. Recommended nitrogen rates for switchgrass vary by region because of length of the growing season and precipitation but will likely not exceed the rates per kilogram of biomass yield applied in this study. In some previous analyses, diesel fuel requirements were based on a linear function of biomass yield (10). This assumption underestimates diesel requirements in conditions with low biomass yield and overestimates diesel requirements under conditions with moderate to high biomass yields, because certain agricultural practices, such as planting, herbicide applications, and fertilizer applications, have a fixed diesel usage requirement regardless of yield. Diesel requirements increase with increased biomass yields at the harvesting stage but not at the previously estimated rates. Agricultural energy inputs for the switchgrass fields based on actual farm inputs [see supporting information (SI) Tables 1 and 2] were lower than in previous switchgrass life cycle analysis studies (8, 10, 14), because diesel usage, fertilizer requirements, electricity rates, and machinery costs in the previous studies were largely based on estimated values (Fig. 2).

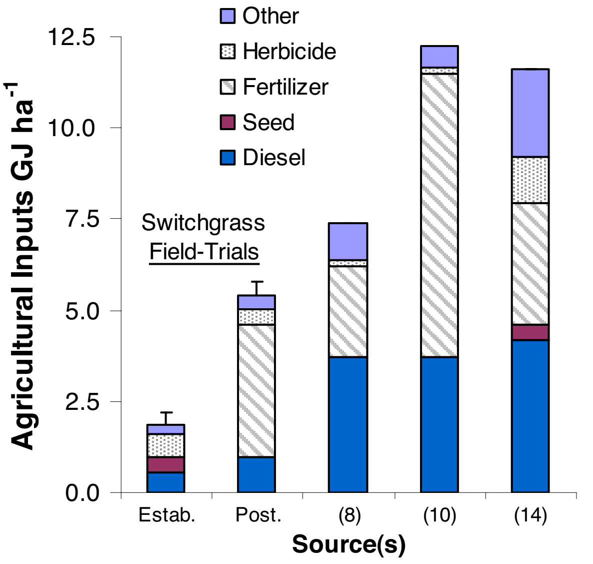

Fig. 2. Switchgrass agricultural inputs (GJ·ha^{-1}) from the establishment year (Estab.) and postplanting harvest years (Post.) in a multilocation farm trial using known farm inputs. Agricultural inputs used were the embodied energy of switchgrass seed, fertilizer, herbicide, diesel, and other energy (farm machinery, farm labor, product transportation, electricity, and product packaging). Results are compared with agricultural input data from switchgrass energy balance studies (8, 10, 14) based on small plot data and input estimates.

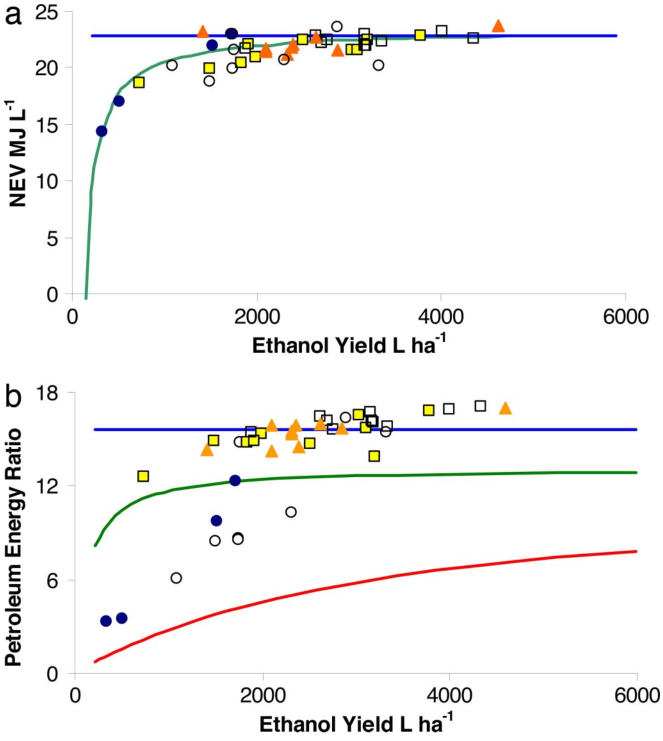

Fig. 3. Energy estimates for 10 switchgrass fields managed for bioenergy for the establishment year (filled circle) and second (open circle), third (yellow square), fourth (open square), and fifth years (red triangle), using input and biomass production data from 10 farms in the EBAMM model (9). (*a*) Comparison of net energy values (MJ·liter^{-1}) from the fields based on known agricultural inputs with estimates from two simulated switchgrass studies (8, 10). NEV are not shown for one study (14), because they were negative for switchgrass at all ethanol yields due to the misassumption that nonrenewable energy will be used for all biorefinery energy needs. (*b*) PER, which is the biofuel output (MJ) divided by the petroleum (MJ) requirements for the agricultural, biorefinery, and distribution phases, for the 10 fields compared with three simulated studies (8, 10, 14). Blue line, Wang (10); green line, Farrell *et al.* (8); and red line, Pimental and Patzek (14).

NEV. The NEV (output energy–input energy) from switchgrass in the Great Plains varied with year of production and ethanol yield but exceeded 14.5 MJ·liter^{-1} ethanol for all harvest years (Fig. 3*a*). NEV were consistent across locations, averaging 21.5 MJ·liter^{-1} ethanol (Fig. 3*a*; see also SI Table 3). These results were intermediate to previously simulated switchgrass energy balance studies (8–10). Ethanol yield was sensitive to climatic conditions and stand age more than agricultural inputs, which differs from a prior study (10) that assumes a linear response of switchgrass ethanol yield to agricultural inputs (Fig. 3*a*). Based on regression analysis, the NEV was linearly related to ethanol yield in the establishment year and in the third harvest year only [establishment year, NEV = 13.86 + 0.0054(EtOH yield), $P <$ 0.02, $R^2 = 0.96$; harvest year 3, NEV = 18.41 + 0.001(EtOH yield), $P < 0.001$, $R^2 = 0.74$]. Fields with low biomass yields caused by weather, deviations from recommended agronomic practices, or fields not harvested in the establishment year had lower initial NEV than better-managed fields without drought-induced establishment problems. Switchgrass, a perennial, does not achieve full biomass yield potential until one to two growing seasons after establishment. Proper agronomic practices with normal climatic conditions can result in establishment year biomass yields of 50% of full yield potential. Switchgrass, in long-term evaluations (>10 yr), has been shown to have consistent biomass yields over time when stands are mature (15).

A previous study (14) reported a negative energy balance for ethanol derived from switchgrass by assuming that high levels of agricultural inputs (Fig. 2) would be required, and that nonrenewable energy would be needed to generate power for a cellulosic ethanol biorefinery. Feasibility research indicates that the lignaceous portion of plant biomass remaining after saccrification and fermentation can be used to power the cellulosic ethanol biorefinery and potentially could be used to generate additional electricity to sell to the electrical grid as a byproduct (16–18).

PER. Bioenergy efficiency was also evaluated as an ethanol output (MJ)/petroleum input (MJ) ratio (PER) for the production, refining, and distribution phases. All previous switchgrass studies have reported (8–10, 14) that, under most ethanol yield projections, the amount of energy from ethanol produced from switchgrass biomass exceeds petroleum consumed (Fig. 3*b*). In this multifarm trial, switchgrass produced an estimated average 13.1 MJ ethanol for every MJ of petroleum input (Fig. 3*b*). Our analysis showed that at ethanol yields of ≥3,500 liter·ha^{-1}, PER surpassed all previous estimates (8–10, 14). Establishment and second-year stands had the lowest PER, a result of tillage, seeding, and harvesting energy costs with reduced biomass yields. There was a linear relationship between ethanol yield and PER for all harvest years. However, linear trends by harvest year declined over time, suggesting that, on mature fields, PER will be consistently high and vary little by ethanol yield. [For the establishment year, PER = 0.71 + 0.0064(EtOH yield), $P < 0.01$, $R^2 = 0.98$; harvest year 2, PER = 1.81 + 0.0046(EtOH yield), $P < 0.01$, $R^2 = 0.68$; harvest year 3, PER = 12.75 + 0.001(EtOH yield), $P < 0.02$, $R^2 = 0.51$; harvest year 4, PER = 14.42 + 0.0006(EtOH yield), $P < 0.05$, $R^2 = 0.55$; and harvest year 5, PER = 13.34 + 0.0008(EtOH yield), $P < 0.01$, $R^2 = 0.62$.]

NEY from Perennial Bioenergy Systems. Net energy gains or NEY per hectare of biofuels are affected by crop yield, conversion rate, and energy inputs required to produce, deliver and process feedstock [NEV (MJ·liter^{-1}) × biofuel yield (liter·ha^{-1})]. Previous small plot research (19) estimated that human-made prairies grown in Minnesota on marginal land produced more biomass energy (Fig. 4*a*) than switchgrass grown with low management inputs resulting in a higher NEY (Fig. 4*b*). Assuming an estimated conversion rate of 0.38 liter·ethanol·kg^{-1} harvested biomass (9), the results of these field-scale farm trials demonstrate that switchgrass managed for biomass yield with moderate levels of inputs including N fertilizer, produced an estimated 93% more ethanol per hectare than reported estimates for human-made prairies and 471% more ethanol per hectare than low-input switchgrass grown in the adjacent state of Minnesota (Fig. 4*a*). Annual biomass yields of established switchgrass fields averaged 5.2–11.1 Mg·ha^{-1} (SI Table 4). Estimated mean NEY on established switchgrass fields was 60 GJ·ha^{-1}·y^{-1}, which was 93% greater than human-made prairies and 652% greater than low-input switchgrass (Fig. 4*b*) grown in small plots (19). Switchgrass managed as a bioenergy crop in these field trials had estimated ethanol yields similar to those for corn grain (Fig. 4*a*) grown in the same states and years. Caution should be made in making direct ethanol yield comparisons with cellulosic sources and corn grain, because corn grain conversion technology is mature, whereas cellulosic conversion efficiency technology is based on an estimated value (9). However, mean corn grain yield (20) from Nebraska, South Dakota, and North Dakota used in this analysis is based on irrigated and rain-fed fields on both fertile and marginal soils. Switchgrass will likely be established on rain-fed marginal soils, where row crop yields are generally lower and more variable than crop yields on irrigated or rain-fed fertile soils. Even with a more conservative cellulosic conversion value, switchgrass from this study is much closer to current corn grain ethanol yields than human-made prairies for this geographic region.

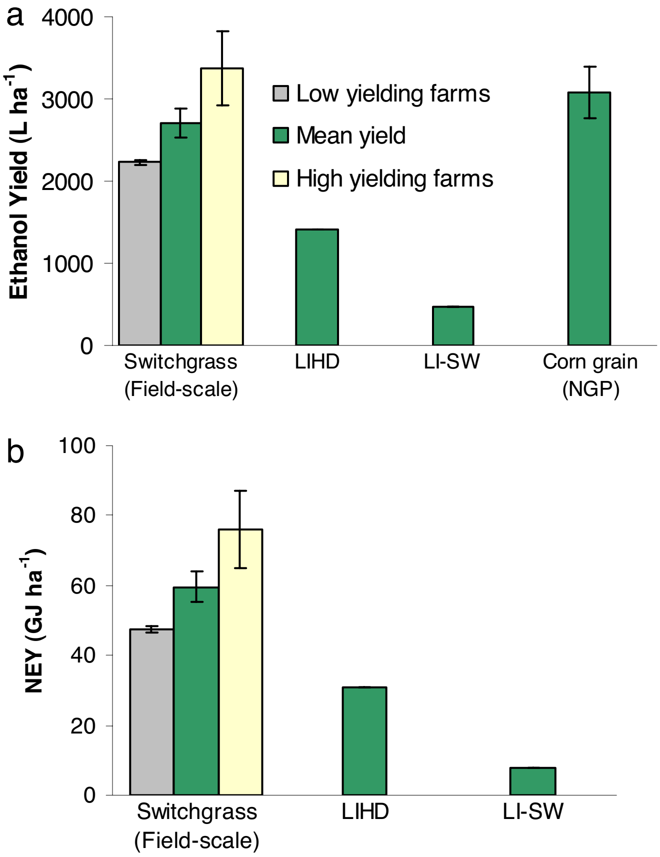

Fig. 4. Comparison of estimated ethanol yield and NEY from switchgrass fields managed as a bioenergy crop; low-input, high-diversity, human-made prairies (LIHD) on small plots (19); low-input switchgrass (LI-SW) small plots (19); and corn grain yields (ref. 20; 2000–2005) from Nebraska and South and North Dakota). (*a*) Mean ethanol yield (liter·ha^{-1}) was greater for the three farms with low mean ethanol yields, mean ethanol yields of all farms, and three farms with high mean ethanol yields (≥2 yr after seeding) or established switchgrass plots (≥9 yr after seeding) grown in a higher precipitation zone and was comparable to corn grain ethanol yields for the three states. Conversion of corn grain and cellulosic biomass to ethanol was estimated at 0.4 liter·kg^{-1} and 0.38 liter·kg^{-1}, respectively (9). (*b*) NEY from established switchgrass fields for all farms was consistently higher than human-made prairies or low-input switchgrass (19) grown in a higher precipitation zone.

GHG Emissions. Life-cycle analysis models have quantified the amount of either GHG emitted from ethanol or GHG displaced by shifting to an ethanol energy source from a petroleum energy source (8, 10, 21–23). For switchgrass, studies have estimated the amount of GHG displaced by the amount of harvested material that is converted to ethanol (8, 10, 23). Others have determined the amount of GHG displaced by the amount of harvested

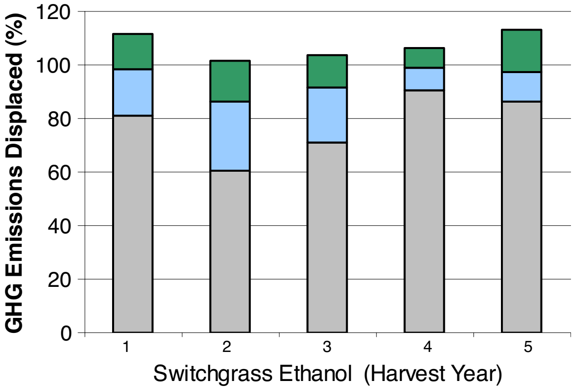

Fig. 5. Estimated displacement (%) of GHG emissions by replacing conventional gasoline (baseline) with cellulosic ethanol derived from switchgrass. Minimum (grey), mean (blue), and maximum (green) percent GHG displacement for each switchgrass harvest year is based on actual production data from 10 switchgrass fields. Estimated GHG values include the amount of CO_2 sequestered in the soil (100 yr) by switchgrass, which was estimated to be 138.1 kg of CO_2 Mg^{-1} of aboveground biomass yr^{-1} (28).

material and by the amount of carbon dioxide sequestered into the soil profile (24, 25). The amount of soil carbon sequestration by reintroduction of perennial grasses to a field depends on existing soil C concentration, soil type, climate, precipitation, management, and annual biomass production (26, 27). Soil carbon levels on low-input switchgrass fields (29 soil types) have been shown to increase over time, across soil depths, and are higher than adjacent cropland fields in the Northern Plains (26). Switchgrass managed for bioenergy on multiple soil types in the Northern Plains was carbon-negative, sequestering 4.42 Mg C $ha^{-1}\cdot y^{-1}$ into the soil profile (27). In this analysis, the amount of GHG emissions displaced using ethanol from switchgrass over conventional gasoline was estimated based on biomass yields by both fossil fuel displacement (9) and the estimated carbon dioxide sequestered as soil C for 100 yr by switchgrass on converted cropland (28).

Life-cycle analysis estimated that ethanol from switchgrass averaged 94% lower GHG emissions than from gasoline (Fig. 5; see also SI Table 5). Switchgrass fields were GHG-positive, -neutral, or -negative, depending on agriculture input amounts (mainly N fertilization) and subsequent biomass yields. Three of the 5 harvest yr showed farms averaging near-GHG neutral levels. GHG emissions of ethanol from switchgrass, using only the displacement method, showed 88% less GHG emissions than conventional gasoline (8). The use of lignaceous biomass residue for energy at a cellulosic biorefinery is the main reason why switchgrass (8) and human-made prairies (19) have theoretically lower GHG emissions than biofuels from annual crops, where processing energy currently is derived from fossil fuels (11).

Discussion

In this study, we used actual farm information to determine energy inputs. The lower energy inputs for biomass we are reporting in comparison to the estimates reported previously clearly highlight discrepancies that can occur when analyses are based on small-scale research plots and misassumptions. In the prairies of the U.S., precipitation and species richness follow an east–west gradient, with highest levels of precipitation (Fig. 1) and species richness (29) occurring in the east. Mean aboveground net primary production of grassland systems and mean annual precipitation have a positive correlation ($r = 0.90$) for the Great Plains (30). In this study, farms in the east produced greater switchgrass biomass yields than farms in the western part of the study region. Based on precipitation, the low-input prairie in Minnesota was in a higher biomass production zone than the fields in this trial. In addition to having low net-energy yields, the Minnesota prairie plots (19) represent an artificial system, because they were hand-seeded, hand-weeded, and irrigated during establishment; only 10-cm-wide strips within a plot were hand-harvested to determine biomass yields; and the same strips were never reharvested. Low-input subsistence agriculture has low outputs, because essential factors needed to optimize capture of solar energy are lacking. The addition of nitrogen to undisturbed and restored high-diversity prairies has been shown to increase above-ground biomass production (31, 32). These results demonstrate a similar situation likely exists for perennial biomass energy crops. Switchgrass managed as a biomass energy crop with moderate inputs including N fertilizer can be as net energy efficient as low-input systems but can produce significantly greater quantities of energy per unit of land.

For an alternative transportation fuel to be a substitute for conventional gasoline, the alternative fuel should (*i*) have superior environmental benefits, (*ii*) be economically competitive, (*iii*) have meaningful supplies to meet energy demands, and (*iv*) have a positive NEV (11). The results of this study demonstrate that switchgrass grown and managed as a biomass energy crop produces >500% more renewable energy than energy consumed in its production and has significant environmental benefits, as estimated by net GHG emissions as well as soil conservation benefits (1). In this study, we used a constant previously published conversion rate. It is expected that biomass conversion rates will be improved in the future because of both genetic modifications of biomass feedstocks and improvements in conversion technology, which should result in improvement in net energy for switchgrass. Compared with low-input prairies, switchgrass grown and managed as a biomass energy crop can produce significantly greater biomass per hectare, which makes it a more feasible system for providing meaningful supplies of biomass to meet energy demands; it also has fully equivalent NEV.

Current corn production has increased 160% in the U.S. in the last 40 yr because of increased grain yields and expansion of crop area (2). In Iowa, corn grain yields increased >80 $kg\cdot ha^{-1}$ per year during the period from 1930 to 1994 (33). Approximately 50% of the increase in grain yield of corn during this period was attributable to improved hybrids, whereas the remaining improvement was due to improved management practices and inputs. Only a fraction of the research effort that has produced these significant improvements in corn genetics and management has been available for switchgrass and other potential perennial herbaceous biomass species. This is a baseline study that represents the technology available for switchgrass in 2000 and 2001, when the fields were planted. It clearly demonstrates that managed switchgrass production systems have the potential to produce significantly more energy than is used in production and conversion. Traditional breeding techniques have increased yield performance of switchgrass by 20–30% from existing parent types (34). It is expected that further improvements in both genetics (hybrid cultivars, molecular markers) and agronomics (production system management practices and inputs) will be achieved for dedicated energy crops such as switchgrass, which will further improve biomass yields, conversion efficiency, and NEV (35). As an indicator of the improvement potential, switchgrass biomass yields in recent yield trials in Nebraska, South Dakota, and North Dakota (36–38) were 50% greater than achieved in this study. The Green Revolution greatly enhanced the capacity of agriculture to increase food supplies throughout the world by the use of improved genetics and management inputs (39). Green energy goals of nations likewise can be met in part through improved genetics and agronomics. The environmental and ecological effects of the conversion of cropland to CRP were largely positive. It is expected that results will be similar for conversion of land to perennial grasses such as switchgrass for bioenergy. However, environmental and ecological assessments should continue to be made at both the micro and macro scales.

Methods

Locations. We conducted trials on 10 farms in the northern Great Plains for 5 yr to obtain field-scale production information for use in net energy and economic analysis. The 10 farms were located in areas where previous economic model analyses indicated switchgrass grown as a biomass energy crop would be economically feasible (40). The cooperating farmers and farms and fields used in this study were selected based on recommendations of U.S. Department of Agriculture Natural Resource Conservation Service (USDA-NRCS) staff for the three states and site visits by K.P.V. The USDA-NRCS provides technical land eligibility determinations, conservation planning, and practice implementation for the CRP. Rainfed fields represent a range of biomass production environments that occur in this geographical region and have marginal cropland characteristics that could have qualified them for enrollment in the CRP. Adapted switchgrass cultivars were grown and managed as a biomass energy crop in fields on four farms each in Nebraska and South Dakota and two farms in North Dakota using management practices developed in previous research (41). Farms are identified by the name of the nearest town (Fig. 1). The selected switchgrass cultivars were developed primarily for use in pastures. Seeding rates were based on pure live seed (PLS) per unit area (30 PLS m^2), which was $\approx$10 kg·ha^{-1}. The Nebraska fields were established in 2000, except for the Atkinson field, which was reestablished in 2001 because of drought conditions in 2000. The South and North Dakota fields were established in 2001. Total area planted to switchgrass was 67 ha.

Fields used in this study were existing cropland being used for grain or oilseed production. Soil samples were taken on each field before switchgrass establishment to assess initial soil fertility and quality. Field sizes, soil characteristics, and previous cropping history are described (42). Field size ranged from 3 to 9.5 ha and averaged 6.7 ha. Cooperating farmers, who were paid for their work and land use, documented all production operations and machine-harvested field biomass yields. A U.S. Department of Agriculture agronomist visited each field at least twice during each growing season to monitor switchgrass management, stands, and biomass yields. In midsummer, before harvest, 1.1-m^2 quadrants were clipped at 16 locations within each field, and the harvested samples were dried and weighed to verify machine-harvested yields. In our analysis, fields not harvested in the establishment year had their previous agricultural energy inputs added to the first harvested year.

After a killing frost, fields with yields $>$1.1 Mg·ha^{-1} and with minimal weed populations were harvested in the establishment year. Harvesting costs would exceed biomass value for yields below this threshold value. After the establishment year, cooperators had the option to harvest at emerged inflorescence to postanthesis stage of development or after a killing frost. Most cooperators chose to harvest at emerged inflorescence to postanthesis (early to mid-August) in postestablishment years, except for the Bristol, SD, and Munich, ND, farmers, who harvested after a killing frost. Harvests were done with conventional hay equipment. Modern balers are engineered to deliver very uniform bales, so cooperators weighed a subset of bales for yield determinations and sampled the bales with a provided bale-coring probe to obtain bale samples for determining baled biomass dry matter concentration. All yields were adjusted to a dry-weight basis.

Life Cycle Bioenergy Analysis. Energy and Resources Group Biofuel Analysis Meta-Model (EBAMM) calculates cellulosic (switchgrass) agricultural inputs and yields based on previous switchgrass small-plot research, modeled transportation costs, embodied energy of ethanol plant materials, and current agricultural inputs for corn (9, 10, 14, 34, 43). We were able to update EBAMM in this study by: (*i*) basing agricultural diesel consumption on actual field operations, (*ii*) eliminating agricultural electricity use based on known inputs, (*iii*) basing embodied energy of farm machinery on field operations, (*iv*) basing packaging energy on the material that was used, (*v*) incorporating switchgrass seed energy costs, and (*vi*) crediting carbon sequestered by switchgrass to GHG emissions based on field-scale yields (see SI Table 2). A hydrolysis/fermentation biorefinery was the model cellulosic ethanol plant for EBAMM, with cogeneration power/export being the average of a steam Rankine cycle power system and a gas turbine combined cycle system (9, 44). Energy output was based on the ethanol energy value of 21.2 MJ·liter^{-1} (low heating value) and an electricity export of 4.79 MJ·liter^{-1}. In this analysis, biorefinery energy, ethanol conversion yield, and byproduct energy were kept constant, whereas agricultural inputs and crop yield varied by field and harvest year.

Seed energy values were based on agriculture inputs from U.S. Department of Agriculture–Agriculture Research Service (USDA-ARS) (Lincoln, NE) switchgrass seed fields (see SI Table 6). Agricultural inputs from any nonharvest year were added to the first harvestable year to determine NEV, NEY, PER, and GHG displacement. Farmers at individual locations did not report diesel consumption but reported all field operations. Farm machinery was considered the same across all locations to make comparisons among locations (see SI Tables 2 and 7). Any tillage inputs in the establishment year were added to the embodied energy and diesel use requirements for each location. Biomass production system diesel use was estimated based on the number and type of field operations at each location in a given year (see SI Table 7). Nitrogen fertilizer rates recommended to farmers in this study were 10 kg of N per Mg·ha^{-1} of expected yield (45) with a recommended maximum of 112 kg·ha^{-1}·y^{-1}. Nitrogen fertilizer application varied by postestablishment harvest years and locations because of farmer management decisions based on soil moisture conditions. Applied N ranged from 0 kg·ha^{-1} to 212 kg·ha^{-1} with a mean application rate of 74 kg·ha^{-1}·yr^{-1} across all farms (harvest years 2–5). Farm labor energy was included in farm machinery costs and was not separated into an individual agricultural input. Agricultural inputs used for the human-made prairie study were based on reported values from a previous study (19). Agricultural inputs and yields from the human-made prairie study were inserted into EBAMM to make accurate comparisons among studies. A default energy requirement in EBAMM for bale transportation to a cellulosic biorefinery was removed from the human-made prairie study to eliminate duplication. Corn grain yields for Nebraska are from 2000 to 2004, whereas South and North Dakota corn grain yields are from 2001 to 2005 (20).

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