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Meeting US biofuel goals with less land: the potential of Miscanthus

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Abstract

Biofuels from crops are emerging as a Jekyll & Hyde – promoted by some as a means to offset fossil fuel emissions, denigrated by others as lacking sustainability and taking land from food crops. It is frequently asserted that plants convert only 0.1% of solar energy into biomass, therefore requiring unacceptable amounts of land for production of fuel feedstocks. The C_4 perennial grass *Miscanthus* × *giganteus* has proved a promising biomass crop in Europe, while switchgrass (*Panicum virgatum*) has been tested at several locations in N. America. Here, replicated side-by-side trials of these two crops were established for the first time along a latitudinal gradient in Illinois. Over 3 years of trials, *Miscanthus* × *giganteus* achieved average annual conversion efficiencies into harvestable biomass of 1.0% (30 t ha^{-1}) and a maximum of 2.0% (61 t ha^{-1}), with minimal agricultural inputs. The regionally adapted switchgrass variety Cave-in-Rock achieved somewhat lower yields, averaging 10 t ha^{-1}. Given that there has been little attempt to improve the agronomy and genetics of these grasses compared with the major grain crops, these efficiencies are the minimum of what may be achieved. At this 1.0% efficiency, 12 million hectares, or 9.3% of current US cropland, would be sufficient to provide 133×10^9 L of ethanol, enough to offset one-fifth of the current US gasoline use. In contrast, maize grain from the same area of land would only provide 49×10^9 L, while requiring much higher nitrogen and fossil energy inputs in its cultivation.

Keywords: biomass, ethanol, feedstock, perennial, petroleum, production, switchgrass, yield

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Introduction

Over 7.5 million barrels of petroleum were consumed in the US in 2005 (Hill *et al*., 2006), leading to the emission of approximately 2.585 Tg of CO_2, or nearly half of the nation's energy-related CO_2 emissions. The Advanced Energy Initiative (AEI) of the US Government proposes the displacement of 30% of 2005 petroleum use in the transportation sector with domestically produced renewable bioethanol in the coming decades (Milliken *et al*., 2007). This shift from fossil fuel to domestic renewable fuels will likely have major agricultural and environmental implications, but could decrease net carbon emissions from combustion of petroleum by 0.775 Tg.

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Currently, US ethanol used as fuel is obtained by fermenting maize grain (Hill *et al*., 2006). Maize grain is the major current source of ethanol globally. The US is currently the major producer at 20×10^9 L in 2006 (DOE, 2007). The AEI envisages the development of efficient ethanol production by utilizing the cellulose and hemicellulose from perennial grasses, wood chips and agricultural residues (Milliken *et al*., 2007). There are two reasons for turning to this new source. (1) Maize production in the US is insufficient to meet the renewable fuel target. Maize grain ethanol supplied <2% of the 2004 transportation energy demand (Davis & Diegel, 2004), and even if all maize grown currently in the US were fermented for ethanol production, it would supply only 12% of today's gasoline use (Hill *et al*., 2006). (2) Maize is an annual crop and though productive, requires large annual energy and financial inputs including tillage and planting, energy intensive nitrogen fertilizer, herbicides and pesticides. As a result, ethanol from maize grain has only a small net positive carbon balance (Farrell *et al*., 2006).

To make up for the shortfall in ethanol from maize grain, AEI calls for the development of cellulosic ethanol technology to be economically competitive by 2012 (Milliken *et al*., 2007). While annual crops can be used for cellulosic ethanol production, greater efficiencies can be realized from perennial species grown as dedicated energy crops because their reduced need for annual cultural inputs minimizes fossil fuel use in production and improves the overall energy balance of the fuel (Hill *et al*., 2006; Ragauskas *et al*., 2006).

Recent work suggests the use of restored prairies to sustainably produce $4\,\mathrm{t\,ha^{-1}\,yr^{-1}}$ (Tilman *et al*., 2006). As perennials, these so-called low-input high-diversity (LIHD) systems need only be planted once, and require minimal cultivation or fertilization. Each spring, nutrients are translocated from the perennial root system to the growing shoot (Beale & Long, 1997). In autumn, the nutrients are returned to the root system, before the annual crop of shoots is harvested so that the nutrients are retained by the system and only the carbohydrate fuel feedstock is removed (Heaton *et al*., 2004a, b; Dubeux *et al*., 2007). This late harvest also allows many animals, such as nesting birds, to complete their life cycle without disturbance (Semere & Slater, 2007). Steppe, pampas and savannah ecosystems have similar growth patterns, and are therefore also potential sustainable sources of lignocellulose.

Taking the US as an example, at $4\,\mathrm{t\,ha^{-1}}$ over 90 Mha of restored prairie would be required to provide sufficient feedstock to replace just one-fifth of current gasoline use; this assumes a conversion of dry biomass into ethanol of $380\,\mathrm{L\,t^{-1}}$ (DOE, 2006; Anex *et al*., 2007). This area would exceed the total area currently occupied by the three current largest users of US cropland: maize, soybean and wheat (USDA, 2007). The low yield per unit area would also result in high costs of harvest and require long transportation distances between the field and the processing station (Fales *et al*., 2007). A compromise may be pure stands of the most productive perennial species with the 'prairie' life form. These would provide the sustainability of natural prairie, but should require less land area for large-scale ethanol production (Fales *et al*., 2007; Hill, 2007).

A joint study by the US Department of Agriculture (USDA) and Energy (DOE), commonly called the 'billion-ton study', has estimated that 1×10^9 t of plant biomass will be required annually to meet the AEI renewable targets (Perlack *et al*., 2005). This vast amount of biomass is not currently available from US agricultural and forestland without disruption of food production. However, assuming key changes in current practices, it is projected that 1.366×10^9 dry tons of biomass could be available annually by 2030 without impacting food production (Perlack *et al*., 2005). Of this, forest residues would contribute 368 million tons, and 998 million tons would be generated from 181 million hectares of agricultural land. Within this agricultural land, 377 million tons would come from conversion of 24 million hectares of active and currently idle US farmland to perennial energy crops (Perlack *et al*., 2005). This proportion demonstrates why perennial energy crops are favored – their use enables 38% of the needed biomass to be produced from only 13% of the agricultural land. It must be recognized, however, that even 24 million hectares is a vast quantity of land, an area roughly the size of Oregon, and more than the total area of the US planted to wheat in 2006 (USDA-NASS, 2006).

It is implied that most of the 24 million hectares of energy crops envisioned in the billion-ton study would be planted to switchgrass (*Panicum virgatum* L.) (Perlack *et al*., 2005). Switchgrass is a large perennial grass native to the North American prairie that has been historically used as forage. It was chosen by the DOE for development as a model herbaceous energy crop in 1991 with the main goal of identifying high-yielding varieties in trials located throughout the Southeast and Southern Great Plains of the US (McLaughlin, 1992; Sanderson *et al*., 1996). A review of this effort lists observed biomass productivity among cultivars and locations ranging from 9.9–$23.0\,\mathrm{t\,ha^{-1}}$ in research trials, with an average of $13.4\,\mathrm{t\,ha^{-1}}$ (McLaughlin & Kszos, 2005). A major assumption of the billion-ton study was that continued breeding efforts will increase switchgrass yields by ca. 60% to an average of $20\,\mathrm{t\,ha^{-1}}$ by 2030 (Perlack *et al*., 2005). This improvement would also counter one of the major criticisms of biomass energy i.e. that its efficiency of conversion of solar energy, claimed to be just 0.1%, is too low to provide any significant solution to carbon replacement (Hoffert *et al*., 2002; Service, 2005; Pimentel & Patzek, 2006).

While the DOE chose switchgrass as a model energy crop, European research and implementation has focused on another large perennial grass, *Miscanthus × giganteus* Greef et Deu ex. Hodkinson et Renvoize (Hodkinson & Renvoize, 2001); hereafter called Miscanthus. Miscanthus is a naturally occurring sterile hybrid and all trials were planted with the same clone (Linde-Laursen, 1993; Christian & Haase, 2001). Beginning in 1992, Miscanthus trials were undertaken at 16 locations throughout 10 European Union countries as part of the EU Miscanthus Productivity Network (Jones & Walsh, 2001). Results of these and additional trials indicate harvestable Miscanthus yields range from 10–$40\,\mathrm{t\,ha^{-1}}$ throughout Europe (Lewandowski *et al*., 2000).

Because Miscanthus has mainly been tested in Europe and switchgrass in the US, biomass yields from mature stands of Miscanthus and switchgrass grown side by side are not available in the peer-reviewed literature. However, a quantitative review extracted values of annual production from peer-reviewed articles describing the separate trials of these species (97 observations of Miscanthus, 77 observations of switchgrass) and suggested that Miscanthus produced an average peak annual biomass of $22\,\mathrm{t\,ha^{-1}}$ compared with $10\,\mathrm{t\,ha^{-1}}$ of switchgrass (Heaton *et al*., 2004b). The yield advantage of Miscanthus appeared consistent regardless of rainfall, nitrogen fertilizer or growing degree days.

A model developed from European studies of Miscanthus (Clifton-Brown *et al*., 2000, 2004) was used to explore the likely productivity of Miscanthus in Illinois (Heaton *et al*., 2004a). Illinois is a major agricultural state in the Midwestern United States with 11 million hectares of farmland and is typical of much of the Midwest (USDA, 2007). Modeled projections of Miscanthus peak annual biomass (before senescence) ranged from 27 to $44\,\mathrm{t\,ha^{-1}}$ in Illinois (Heaton *et al*., 2004a).

Literature review and modeled yield projections, therefore, indicated Miscanthus as a promising energy crop for the Midwest with yields that would exceed the DOE model species, switchgrass, but this promise has been heretofore untested in side-by-side replicated field trials in the US. While the Midwest may be at similar latitudes to Western Europe, its climate and soils differ significantly. The previous desk studies may therefore leave important questions unanswered. Will the model predictions apply in the more continental and severe climate of the Midwest? Will the crop survive the colder winters? Will biomass losses during the winter be as slight as in W. Europe? The present study aimed to use multiple field trials to provide actual comparative measures of Miscanthus and switchgrass biomass production in Illinois. Field trials were located in North, Central and South Illinois, spanning almost 5° of latitude, ca. 5 °C in mean temperature and a range of soils. Though focused in Illinois, results of this research are likely applicable to much of the Midwestern United States, given the similarity of cropland and cropping systems.

The specific objectives of this study were as follows:

1) How does establishment and survival of Miscanthus compare to switchgrass?
2) What is the relative dry matter production of Miscanthus and switchgrass in Illinois?
3) How do Miscanthus and switchgrass differ in the efficiency with which they intercept and convert solar radiation to biomass?

Materials and methods

Trials were located at three University of Illinois Agricultural Research and Education Centers, with a range of mean annual temperatures and precipitation (Table S1). Previously, this land had been planted to rotations of maize (*Zea mays* L.), soybean (*Glycine max* L. Merr.) and wheat (*Triticum aestivum* L.). Daily meteorological data including total solar radiation, temperature, precipitation and pan evaporation were collected within 2 miles of each trial location by the long-term monitoring stations of the Illinois Climate Network (Angel, 2007).

Trial establishment

Field trials of Miscanthus and switchgrass were established at the three locations in May and June of 2002. Four $10\,\mathrm{m} \times 10\,\mathrm{m}$ plots of each species were arranged in a completely randomized design at each location. Planting stock and methods for each species are described as follows.

Miscanthus

Miscanthus × *giganteus* availability has been limited in the US, and the plant is often incorrectly identified. To ensure quality control of planting stock, material for this study was cloned from a single source. This source was a demonstration plot of Miscanthus planted at the University of Illinois Turf and Ornamental Research Center (Urbana, IL) in 1988, which in turn came from the Chicago Botanic Garden (Chicago, IL) (T. B. Voigt, personal communication). AFLP analysis positively identified this clone as the sterile triploid resulting from a cross of *Miscanthus sinensis* and *Miscanthus sacchariflorus* and correctly designated as *Miscanthus* × *giganteus* Greef et Deu ex. Hodkinson et Renvoize (John Clifton-Brown, Institute of Grassland and Environmental Research at Aberystwyth, UK, personal communication).

To generate sufficient plants for field trials, Miscanthus rhizomes were dug from the research center in September 2001. These rhizomes were propagated vegetatively in a glasshouse throughout the winter and spring of 2001/2002. Rhizome pieces were cut by hand and placed in 1 l plastic pots in a growth media of 1 : 1 : 1 soil, peat and perlite. Supplemental lighting from high-pressure sodium lamps was used to maintain a minimum 16 h day length once shoots were actively growing. Room temperature was maintained at 25 °C day/20 °C night. Plants were watered daily and fertilized once a week with a liquid fertilizer of 15–5–15 NPK with trace Ca and Mg (Scott's Peters Excel, The Scotts Company, Marysville, OH, USA). As soon as plants developed sufficient new rhizomes, typically 4–6 weeks, they were divided and placed in new 0.5 l pots. In April and May of 2002, plants were hardened outside in a sheltered area for 2 weeks before movement to the field. At planting, each pot contained one to four shoots ranging from 10–50 cm in height. These plants were very similar in size to those used in the EU Miscanthus network trials (Beale & Long, 1995). Soil and plants were removed from the pot and planted at 1 m intervals in rows of 1 m spacing in soil that had been tilled to a depth of 10 cm, following the recommendations of earlier EU trials of Miscanthus (Bullard, 1996).

Switchgrass

P. virgatum L. cv. Cave-in-Rock is an intermediate growth habit switchgrass cultivar indigenous to Illinois and recommended for biomass production in the Midwest (Teel *et al*., 1997). Sowing and seed-bed preparation also followed the recommendations of Teel *et al*. (1997). Weed-free seed with an 82% germination test rate (Sharps Brothers Seed Company of Missouri, Clinton, MO, USA) was broadcast at a rate of at least 13 kg of pure live seed ha^{-1} into a clean seed bed. Before sowing, the plots had been tilled to a depth of 10 cm producing a fine tilth and were lightly packed with a roller. The plots were rolled again following sowing to promote seed to soil contact. Plots were overseeded at the same rate during the winter of 2002/2003 to further ensure adequate stand populations.

Plot maintenance

Details of plot maintenance and care at each site are provided in Table S2. Herbicides were necessary in both species at all locations in the first year, and in some plots in the second. By 2004, weed control was unnecessary in the Miscanthus plots, but still needed for switchgrass plots at the Northern site. By 2005, the spring growth of both species at all sites was sufficiently rapid to quickly shade out any weeds. Beginning with the 2003 growing season, all remaining dead shoots from the prior year's growth were cut with conventional forage harvest equipment in March, the exact equipment varying with location. For example, at the Central location, the crop was mowed and conditioned with a self-propelled windrower (New Holland 2450, New Holland, Grand Island, NE, USA) then gathered into 80 cm × 90 cm × 250 cm bales (New Holland BB-940A, New Holland).

Establishment measurements

In the spring of 2003, emergent Miscanthus plants were counted to determine the mortality rate at all locations. In addition, at the Central location, the height of five tillers and tiller density was assessed at regular intervals in two 0.2 m^2 or two 1-m^2 quadrats randomly placed in each plot of switchgrass or Miscanthus, respectively. The different areas reflect the much higher tiller numbers in the switchgrass plots.

Radiation capture

Measures of canopy light interception and leaf area were taken approximately bi-weekly at the Central location from emergence to senescence in 2005 and 2006. Photosynthetically active radiation (PAR, 400–700 nm) was measured in three randomly selected areas in each plot between 10:00 hours and 14:00 hours on clear-sky days with a line ceptometer (AccuPAR LP-80; Decagon Devices Inc., Pullman, WA, USA). Light interception was determined by the fraction of light measured below the canopy compared with that measured above the canopy. A single measurement consisted of one observation of radiation above the canopy followed by four observations from positions across a 0.5 m transect below the canopy. Three measurements were made in each plot at intervals throughout the seasons. Light interception was determined by dividing the average of light measured below the canopy compared with that measured above the canopy (Nobel *et al*., 1993).

Leaf area index (LAI) was measured in combination with light interception using the line ceptometer (AccuPAR LP-80; Decagon Devices Inc.) as described earlier. Using the observations of direct beam sunlight interception, LAI was calculated from the probability that a ray of light would penetrate the canopy, correcting for the zenith angle of the sun and leaf area distribution (Decagon, 2005). Because light might also be intercepted by stem as well as leaf, LAI expressed in this study is actually a measure of the area of all photosynthetic surfaces. The stems of both species were almost completely enclosed by leaf sheath, so that the reported LAI is a combination of leaf lamina and leaf sheath.

The bases of yield differences were further analyzed according to the efficiencies of interception and conversion as defined by Monteith (1977) as used by Beale & Long (1995):

$$Y = S_t \varepsilon_i \varepsilon_c / k_t, \tag{1}$$

where Y is the peak annual aboveground biomass ($kg\,m^{-2}$), S_t the incident PAR from emergence to the time of peak biomass ($MJ\,m^{-2}$), ε_i the efficiency with which that radiation is intercepted (dimensionless 0–1), ε_c the efficiency with which the intercepted radiation is converted to aboveground biomass (dimensionless 0–1) and k_t is the energy per unit biomass ($MJ\,kg^{-1}$) assumed to be 18 $MJ\,kg^{-1}$ as measured by Beale & Long (1995). In addition, efficiency of use of annual solar radiation receipt was calculated by dividing the peak biomass by total annual incident radiation.

Biomass sampling

Procedures for measuring the annual progression of shoot biomass production were modified from Roberts *et al*. (1993) as described by Beale & Long (1995). Plant dry mass per unit ground area was determined for all locations on five dates spread across the annual crop production cycle (June, August, October, December and February) from 2003 to 2005. In 2006, dry mass was determined for the northern and southern sites only in August, December and February. Because of low initial stem density, two 1-m^2 quadrats per Miscanthus plot were subsampled in 2003 and from 0.19 m^2 areas in subsequent years, by which time the stems had occupied the space between the original plantings. Switchgrass subsamples measured 0.19 m^2 throughout the experiment. Quadrats were randomly selected for subsampling from the inner 9 m × 9 m of each plot, effectively leaving a 1.5 m band of guard rows in the mature crop. Light extinction measurements (not shown) indicated no change in light levels past this point in the plot. Subsamples per plot were cut by hand to a 5 cm stubble height and weighed fresh in bulk, on each sampling date. Approximately 0.5 kg of these tillers were selected at random, then oven-dried at 60–70 °C to a constant weight to determine total dry mass. Biomass calculated from subsamples was supported by similar values from the total plot harvest made in February of each year.

Data analysis

All data were analyzed using a mixed model analysis of variance (PROC MIXED, SAS Institute Inc., Cary, NC, USA). Analysis of repeated measures on plots at multiple days of year used a heterogeneous autoregressive model of the variance/covariance matrix structure. Location, year and species were considered fixed variables, while plot was considered a random variable, and significance was determined using the *F*-statistic and $\alpha = 0.05$. For the purpose of making broader inferences from these data, the means across all locations and years for each species were analyzed using a mixed model with species as the only fixed effect, and year and location included as random effects.

Results

Climate conditions

Annual temperatures in the North and Central locations were similar to the long term averages, but were 1–2 °C below average in every year at the South location (Table S1; Fig. 1). Precipitation was considerably below average at the North location with the exception of 2006 and low in 4 out of 5 years at the Central location, with the exception of 2004. Precipitation was above average in 2002 and 2006 at the South location, near average in 2003 and below average in 2004 and 2005. In general, years with lower annual precipitation experienced greater evaporative demand as indicated by potential evaporation (Fig. 1).

Establishment

Following the 2002 establishment year, the over-winter survival of Miscanthus was 86% at the Northern location and 100% at the Central and Southern locations when assessed in the spring of 2003. No further plants were lost in subsequent years. At the Central location, where tiller density and height were measured, switchgrass rapidly produced tillers throughout the spring and summer and produced significantly more tillers than Miscanthus ($P<0.0001$). Tiller density in switchgrass stands reached a seasonal maximum of 797 m^{-2} in September 2003, falling to 542 m^{-2} by October (Fig. 2). Miscanthus conversely produced fewer stems and achieved a maximum tiller density of 110 m^{-2} in May 2003, which was followed by a 30% reduction to 64 tillers m^{-2} over the next month. Though switchgrass tillers were more numerous, they were much shorter than the tillers of Miscanthus (Fig. 2).

Leaf area and radiation capture

Switchgrass intercepted a higher proportion of incident PAR than Miscanthus early in the season but was surpassed by mid-June (Fig. 3). The switchgrass canopy did not achieve canopy closure ($\varepsilon_i \geq 0.95$) in 2005 until 20 days or in 2006 until 10 days after Miscanthus (Fig. 3). Over the entire growing seasons, Miscanthus intercepted slightly, but significantly more light than switchgrass ($P<0.0001$) (Table 1a). Both species then maintained $\varepsilon_i \geq 0.95$ through to senescence. The seasonal maximum interception efficiency ε_i of PAR in 2005 was 0.996 in Miscanthus and 0.966 in switchgrass, while in 2006, maximum ε_i was 0.998 for Miscanthus and 0.958 for switchgrass. Importantly, both crop canopies were intercepting the majority of available PAR by May, and 95% from June through to the onset of senescence in mid-September (Fig. 3).

Patterns of canopy development as indicated by LAI paralleled those of light interception. There was no statistically significant difference in LAI between the two crops until May 24 in 2005 and May 23 in 2006, by

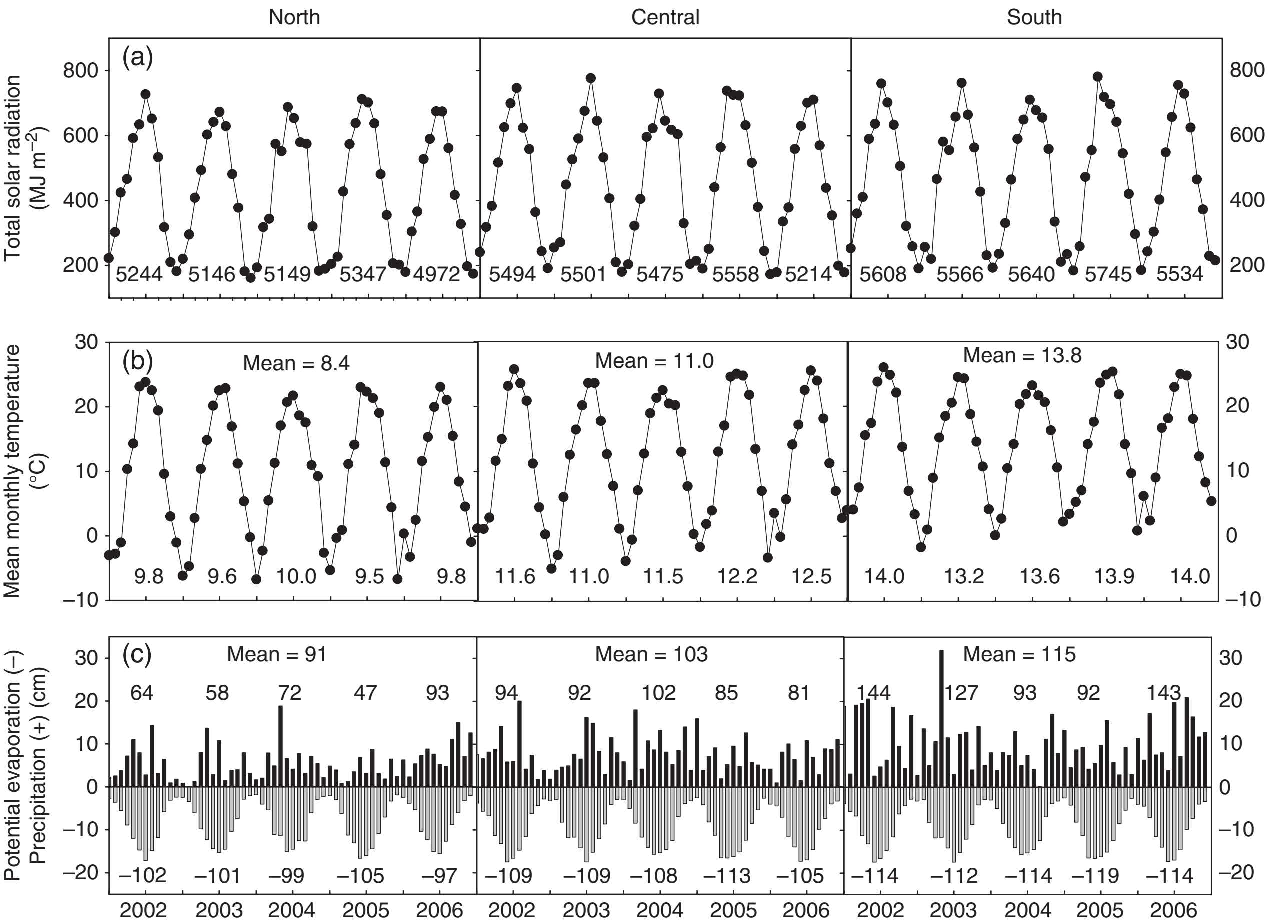

Fig. 1 Climate data collected daily from three monitoring stations of the Illinois Climate Network located at Shabbona ('North'), Urbana ('Central') and Dixon Springs ('South'). (a) Symbols represent cumulative total solar radiation with annual totals listed beneath. (b) Symbols represent monthly mean temperature with annual mean temperature value listed beneath. (c) Positive value bars represent cumulative monthly precipitation with annual total listed above, negative value bars represent potential evaporation measured by pan evaporation with annual totals listed below. Means are 30-year means from 1977 to 2006.

which point Miscanthus LAI was significantly greater ($P<0.0001$) than that of switchgrass (Fig. 3). This difference persisted through to canopy senescence and was statistically significant when averaged over the growing seasons ($P<0.0001$) (Table 1b).

Biomass production and conversion efficiency

Both crops are considered to reach ceiling yields 3 years after planting (Clifton-Brown *et al*., 2001; McLaughlin & Kszos, 2005); 2004 was the third year after planting in the present study. On all sampling dates from 2004 to 2006 and at all sites, dry matter per unit area was significantly greater ($P<0.0001$) for Miscanthus than switchgrass (Tables 1 and 2, Fig. 4a). Peak dry biomass production (H_{max}) of Miscanthus was highest at the Central location in August of 2004 when it reached 60.8 ($\pm$ 2.8) t ha^{-1} (Table 2, Fig. 4c). This corresponded to a peak biomass of 51.3 $\pm$ 2.6 t ha^{-1} in August 2006 at the South location and 38.1 ($\pm$ 5.7) t ha^{-1} at the North location in October 2004 (Table 2, Fig. 4). After full senescence, the measured biomass of Miscanthus in December (H_1) was reduced on average by 33% at the North location, 27% at the Central location and by 18% at the South location (Table 2, Fig. 4a). Peak biomass production by switchgrass occurred in August 2006 at the North location (8.4 $\pm$ 0.9 t ha^{-1}), in August 2004 at the Central location (26.0 $\pm$ 2.8 t ha^{-1}) location and in August 2006 at the South location (9.6 $\pm$ 2.9 t ha^{-1}) (Table 2, Fig. 4). After full senescence, end-of-season biomass production (H_1) for switchgrass was reduced on average by 5% at the North location, 34% at the Central location and by 23% at the South location (Table 2, Fig. 4a).

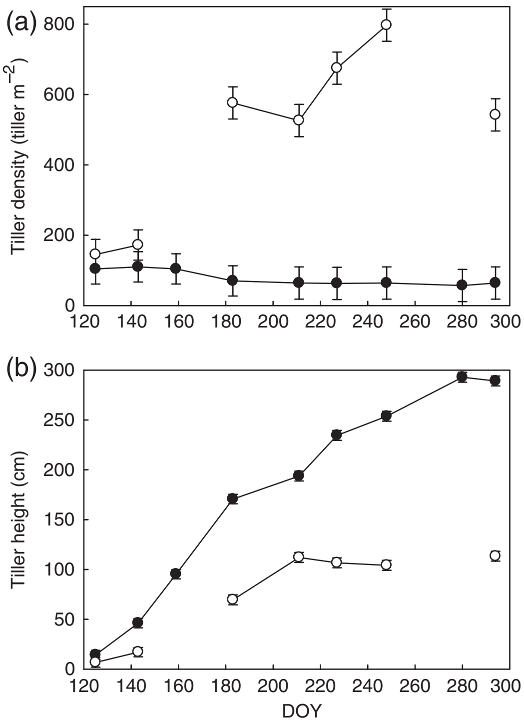

Fig. 2 The seasonal development of tillers during the second year of growth (2003) in Central Illinois ($n = 4$). Symbols represent (a) the density and (b) the height of Miscanthus (•) and switchgrass (○) tillers. Values are least squared means ± 1 SE.

Averaged across all locations, H_{max} of Miscanthus was significantly lower at all sites in 2005 ($P < 0.0001$) and 2006 ($P = 0.0041$) than in 2004, with 2006 being greater than 2005 ($P = 0.0149$) (Fig. 4). End of season dry matter in December was only significantly higher in 2006 ($P < 0.0001$), with no difference between 2004 and 2005 ($P = 0.8522$). The H_{max} of switchgrass in 2005 was substantially higher than in 2004 at the North and South sites, but lower at the Central location (Table 2, Fig. 4). This suggests that switchgrass had not reached its mature yields until the fourth year after planting at the North and South locations. When averaged over all sites, H_{max} and H_1 for switchgrass were higher in 2006 than in 2005 ($P = 0.0275$ and 0.0444, respectively).

Using the PAR-intercepted values measured *in situ* from April 1, 2005 to peak biomass in August, the ε_c of Miscanthus was 0.075 and 0.021 in switchgrass [Eqn (1); Table 3]. When radiation receipt for the whole year is considered, the highest efficiency of conversion was for Miscanthus at the Central location in 2004; 2% for total solar radiation and 4.4% for PAR. Although conditions were exceptional for crop production at the Central location, averaged across all sites and both years Miscanthus still converted 3.1% of the total PAR into biomass and nearly four times the average (0.8%) for switchgrass (Table 4).

Discussion

Three questions were addressed in this study and each is now considered.

How does establishment and survival of Miscanthus compare to switchgrass?

There is considerable experience with the establishment of switchgrass in the Midwest, but no previous research has been conducted with Miscanthus in agricultural trials there until now. Although significant weed control through mowing and chemical application was necessary to establish switchgrass at the three sites (Table S2), yields achieved (Table 2) were comparable to those achieved in other trials (Christian, 1994; Sanderson *et al.*, 1996; Madakadze *et al.*, 1999; Zan *et al.*, 2001). The mean peak biomass of 26 t ha^{-1} at the Central site in 2004 is among the highest recorded for switchgrass.

Miscanthus was established without loss of any plants at the Central and South sites, and 14% loss at the Northern site during the first year. No subsequent losses occurred at any of the sites. This high level of survival was achieved despite average temperatures of −8 to −5 °C for the coldest month, and with 10 cm soil temperatures below freezing from January through early March of the two winters following establishment at the Northern and Central sites. A significant problem in the establishment of Miscanthus in Europe has been loss during cold winters, with 100% losses in some trials (Clifton-Brown & Lewandowski, 2000; Jorgensen *et al.*, 2003). Lewandowski *et al.* (2000) noted that this may represent a major barrier to establishment in continental USA where mean annual temperatures may be similar to Western Europe, but winter minima may be very much lower. The clone planted in these trials survived without any evidence of winter loss in Urbana since 1988 and Chicago since 1970. This includes survival through the coldest winter temperature ever recorded in Chicago, −33.0 °C in January 1985. This survival is in sharp contrast to Clifton-Brown & Lewandowski (2000) who found a 50% mortality of rhizomes at −3.4 °C with the clone planted in European trials. This suggests that either the clone used here may have greater winter hardiness than that used in European trials or the higher aboveground production may allow for the development of larger rhizomes better able to survive the first winter. Importantly, it shows that the low winter temperatures of Illinois are not a barrier to establishment and survival.

Tiller density achieved by Miscanthus in its first year of growth (Fig. 2) was comparable to that in European trials (Bullard *et al.*, 1995). The peak biomass in 2003 of 26 t ha^{-1} (Central) and 21 t ha^{-1} (South), within 14

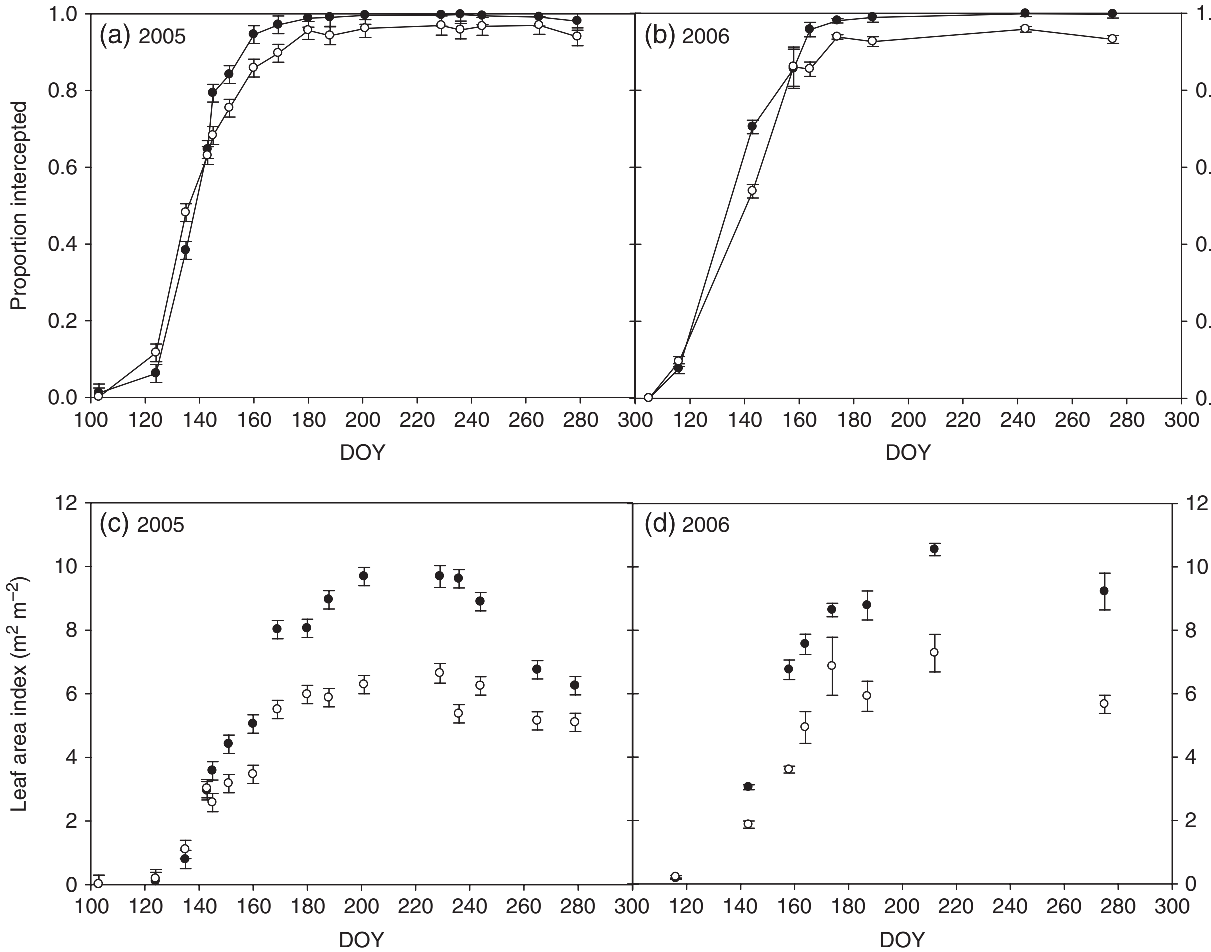

Fig. 3 Interception of incident photosynthetically active radiation (PAR) by Miscanthus (•) and switchgrass (○) canopies in Central Illinois during (a) 2005 and (b) 2006 ($n = 4$). Leaf area development by Miscanthus (•) and switchgrass (○) canopies in Central Illinois during (c) 2005 and (d) 2006 ($n = 4$). Values are least squared means ± 1 SE.

months of planting appears exceptional. These yields already equaled the ceiling yields observed in several European trials at 3 or 4 years after planting (Bullard *et al*., 1995; Himken *et al*., 1997; Lewandowski *et al*., 2000; Clifton-Brown *et al*., 2001).

What is the relative dry matter production of Miscanthus and switchgrass in Illinois?

Ceiling yields were expected to be achieved by both crops within 3 years of planting, i.e. 2004 in this study. Both peak biomass and winter-harvested yields of Miscanthus were significantly greater than switchgrass by a factor of over 4 in 2004. Substantially higher peak biomass yields were achieved by switchgrass in 2005 and 2006 relative to 2004 at both the Southern and Northern trial sites, suggesting that the ceiling yield of this species may not have been achieved within 3 years. Because of this, switchgrass yields for 2004 at the North and South sites, which may underestimate the potential of this species, were omitted from the calculation of the overall mean for each species in Table 2. However, averaged across all sites and all harvest dates in 2005 and 2006, Miscanthus dry matter was still three times that of switchgrass. Switchgrass cv. 'Cave-in-Rock' that originates from and has been recommended for Illinois, was used in these trials. Cultivars 'Alamo' and 'Kanlow,' selected from warmer climates have proved to be more productive. In Iowa, at similar latitude to the present trials, 'Alamo' was 25% more productive than 'Cave-in-Rock' over 4 years (Lemus *et al*., 2002). The yield difference observed between switchgrass and Miscanthus in these side-by-side trials is substantially more than indicated by previous literature comparisons (Lewandowski *et al*., 2003; Heaton *et al*., 2004b). The peak biomass of Miscanthus of 61 t ha^{-1} (Central) and

Table 1 Mixed model analysis of variance associated with (a) interception of photosynthetically active radiation, (b) leaf area index by canopies of Miscanthus and switchgrass in 2005 and 2006 in Central Illinois ($n = 4$, $\alpha = 0.05$), (c) peak and (d) end-of-season total biomass production of Miscanthus and switchgrass at three sites in Illinois during the first 3 years of mature stand production in 2004–2006

Effect	Numerator df	Denominator df	F-statistic	Probability of > F
(a)				
Species	1	144	40.96	< 0.0001
Date	22	144	400.47	< 0.0001
Species × Date	33	144	2.88	< 0.001
Year	1	144	0.46	0.4968
Species × Year	1	144	11.28	0.0010
(b)				
Species	1	144	464.94	< 0.0001
Date	22	144	165.05	< 0.0001
Species × Date	22	144	9.10	< 0.0001
Year	1	144	2.21	0.1395
Species × Year	1	144	3.91	0.0498
(c)				
Species	1	47	305.79	< 0.0001
Site	2	47	24.58	< 0.0001
Species × Site	2	47	9.47	0.0004
Year	2	47	13.94	< 0.0001
Species × Year	2	47	1.75	0.1855
Site × Year	4	47	2.91	0.0314
Species × Site × Year	2	47	1.58	0.2174
(d)				
Species	1	47	177.59	< 0.0001
Site	2	47	16.85	< 0.0001
Species × Site	2	47	3.68	0.0329
Year	2	47	14.27	< 0.0001
Species × Year	2	47	8.07	0.0010
Site × Year	4	47	2.89	0.0319
Species × Site × Year	2	47	0.06	0.9420

49 t ha^{-1} (Southern) in 2004 are among the highest ever recorded for this species (Lewandowski *et al*., 2003; Heaton *et al*., 2004b).

Application of the Miscanthus yield model of Clifton-Brown *et al*. (2000) to Illinois climate data forecasted a mean peak biomass of 27–44 t ha^{-1} (Heaton *et al*., 2004a). Lewandowski *et al*. (2000) speculated that based on European trials, Miscanthus in the central USA would achieve a peak biomass of 20–35 t ha^{-1} which would decline to 13–24 t ha^{-1} by the time of spring harvest in central USA. The present study shows two substantial differences from these forecasts. First, yields were substantially higher with average peak biomass of 33–48 t ha^{-1}. Second, dry mass losses through the winter were 40% at the Northern and Central locations, substantially higher than the loss forecast from European studies. Both findings may reflect the more continental climate of the Midwest with warmer and wetter summers supporting higher production and more severe winters with long periods of freezing causing greater losses of shoot material. This latter point is supported by the fact that winter losses of harvestable dry matter were only 20% at the South location, where winter temperatures were higher (Fig. 1). This finding indicates that recommendations for harvest time in the Midwest will need to be earlier than in Europe, because delaying harvest until after December will result in much greater yield losses.

How do Miscanthus and switchgrass differ in the efficiency with which they intercept and convert solar radiation to biomass?

Analysis of interception and conversion efficiencies provides an insight into why productivity in these two crops was different, and what potential may exist for future improvement. Measurements made throughout 2005 showed that between early May and late August, out of 1367 MJ m^{-2} of available PAR, Miscanthus intercepted 72% and switchgrass 71% (Table 3). Because averaged ε_i was very similar, the difference in yield, therefore, results from a higher ε_c; 0.075 in Miscanthus compared with 0.021 in switchgrass. However, in Texas, an ε_c approaching that observed for Miscanthus has been achieved by switchgrass [calculated from Kiniry *et al*. (1999)]. Theoretical consideration suggests that the maximum ε_c for C_4 photosynthesis is about 0.12 for PAR, after taking account of respiratory losses (Long *et al*., 2006). Although well below the theoretical maximum, 0.075 is among the highest ε_c recorded for any crops (Beadle & Long, 1985) and is about 20% higher than ε_c reported by Beale & Long (1995) for Miscanthus grown in southern England. The higher figure for Illinois may reflect higher growing season temperatures, avoiding low temperature limitation and damage of photosynthesis in England (Naidu & Long, 2004; Farage *et al*., 2006). The difference in ε_c between Miscanthus and switchgrass in Illinois may have multiple causes. First, although ε_i was similar between the two species, switchgrass produced flowers above the canopy in late July. These are pale and reflective and cast a shadow on the leaves below. Miscanthus did not produce flowers until October. Second, leaf photosynthetic rates per unit leaf area were found to be higher in Miscanthus throughout the diurnal cycle and throughout the 2005 growing season by comparison to switchgrass at the Central site (F. G. Dohleman, personal communication). Third, only above-

Table 2 Comparison of mean harvestable dry matter at the time of peak biomass production (H_{max}), and after complete plant senescence (H_1) from Miscanthus and switchgrass grown at three locations in the Midwest USA during 2004–2006 ($n = 4$)

		North		Central		South		State average	
Year	Harvest time	Miscanthus ($t\,ha^{-1}$) ($\pm$ 1 SE)	Switchgrass ($t\,ha^{-1}$) ($\pm$ 1 SE)	Miscanthus ($t\,ha^{-1}$) ($\pm$ 1 SE)	Switchgrass ($t\,ha^{-1}$) ($\pm$ 1 SE)	Miscanthus ($t\,ha^{-1}$) ($\pm$ 1 SE)	Switchgrass ($t\,ha^{-1}$) ($\pm$ 1 SE)	Miscanthus ($t\,ha^{-1}$) ($\pm$ 1 SE)	Switchgrass ($t\,ha^{-1}$) ($\pm$ 1 SE)
2004	H_{max}	38.1 (5.7)	*	60.8 (3.9)	26.0 (3.1)	48.5 (1.8)	*	48.3 (3.5)	26.0 (3.1)
	H_1	13.7 (1.6)	*	25.1 (2.5)	12.8 (1.2)	37.3 (3.0)	*	25.4 (3.2)	12.8 (1.2)
2005	H_{max}	25.6 (1.1)	7.8 (0.6)	40.7 (2.3)	11.5 (1.8)	40.4 (4.1)	7.8 (0.6)	33.3 (2.6)	7.9 (0.8)
	H_1	19.1 (2.3)	7.8 (0.6)	31.1 (3.2)	10.6 (1.3)	27.3 (5.7)	7.8 (0.6)	25.8 (3.8)	7.9 (0.8)
2006	H_{max}	29.9 (3.3)	8.4 (0.9)	44.1 (2.6)	22.0 (5.2)	51.3 (2.6)	9.6 (2.9)	39.0 (4.6)	15.6 (2.6)
	H_1	29.9 (3.3)	7.7 (1.0)	44.1 (2.6)	15.6 (2.6)	39.2 (2.9)	9.1 (2.6)	37.7 (2.4)	15.6 (2.6)
Three-year	H_{max}	31.2 (3.7)	8.1 (0.5)	45.5 (3.9)	19.8 (2.6)	42.3 (3.6)	8.7 (1.8)	**38.2 (2.3)**	**12.5 (1.8)**
average	H_1	20.9 (2.4)	7.8 (0.6)	33.4 (2.8)	13.0 (1.1)	34.6 (2.6)	6.7 (1.1)	**29.6 (1.8)**	**10.4 (1.0)**

*Signifies data is not available for these points. Bold values highlight geographic and temporal averages of both parameters in both species.

ground biomass has been considered in the calculations. Switchgrass may allocate more than 50% of its assimilate to roots (Ma *et al*., 2001), while Beale & Long (1995) found that 39% of the biomass was partitioned to roots and rhizomes in Miscanthus at the end of the growing season.

What do these yields mean in terms of ethanol production? Using the values found here for senesced biomass, assuming conversion of dry mass into ethanol of $380\,L\,t^{-1}$ (DOE, 2006), it would require 34×10^6 ha of switchgrass and 12×10^6 ha of Miscanthus to produce the 2017 target of 133×10^9 L of ethanol annually set by the US Advanced Energy Initiative (Milliken *et al*., 2007; Table 5). Although corn ethanol could also meet this demand (Table 5), it comes at the high environmental price associated with inputs required by annual crops, and at the expense of alternative markets for corn (Cassman *et al*., 2006). Side-by-side trials of mixed prairie, switchgrass and Miscanthus, have not been undertaken and the value cited for prairie here is for a poor soil. However, the number is in line with a detailed survey of natural tall grass prairie peak aboveground biomass which showed a range of yields of $2–7\,t\,ha^{-1}\,yr^{-1}$ across the US (Briggs & Knapp, 1995).

Perennial plants also provide environmental benefits. Though they do not provide the diversity of a full prairie system, perennial grasses with the prairie growth habit do offer a proven sustainable system (Bransby *et al*., 1998; Zan *et al*., 2001; Jones & Donnelly, 2004; Samson *et al*., 2005; Lewandowski & Faaij, 2006). Nitrogen and other nutrients are recycled as they move from the root system into the developing shoot during the spring and then are translocated back to the root system at senescence in the fall. If the dead dry shoots are harvested after this occurs, then the nutrients remain behind, reducing the need for additional fertilizer (Beale & Long, 1997; Dubeux *et al*., 2007). Because of this, the nitrogen content of harvested Miscanthus has been shown to be as low as 0.2% on a dry matter basis (Lewandowski *et al*., 2003). Furthermore, long-term isotopic soil C measurements have shown that Miscanthus stores and retains $0.3–0.5\,t\,C\,ha^{-1}\,yr^{-1}$ making it a candidate for carbon sequestration (Hansen *et al*., 2004; Schneckenberger & Kuzyakov, 2007).

How realistic is it to extrapolate results from three sites to decide a national energy policy? Other locations may have poorer soils and less favorable climates. It has also to be recognized that with most crops, yields achieved on experimental farms with small plots will exceed those achieved in practice on farms (Venendaal *et al*., 1997). However, the yields shown here were achieved with completely unimproved crops and with little knowledge of optimal cultivation methods. Agronomy and genetics have resulted in yield gains of more than threefold in just 50 years with our major food crops (Jauhar, 2006; Reynolds & Borlaug, 2006). Application of these techniques to crops such as Miscanthus at the intensity with which they have been applied to food crops should mean that the seemingly high yields found here are just baselines, and could be expected to increase dramatically in the future (Humphreys *et al*., 2006).

In the longer term, the billion-ton study envisages 24 million hectares planted to perennial energy crops yielding 377 million tons of dry plant mass (Perlack *et al*., 2005). Achieving this yield is dependent on achieving substantial varietal improvement of switchgrass, up to 60%. Miscanthus dry matter across sites and years averaged $30\,t\,ha^{-1}$ in early December harvests in this study (Table 5). If these yields could be achieved more broadly, then the 377 million tons of dry matter could be achieved on 12.6 million hectares, half of the area needed in the billion-ton study projections. Miscanthus is a plant collected from the wild with no

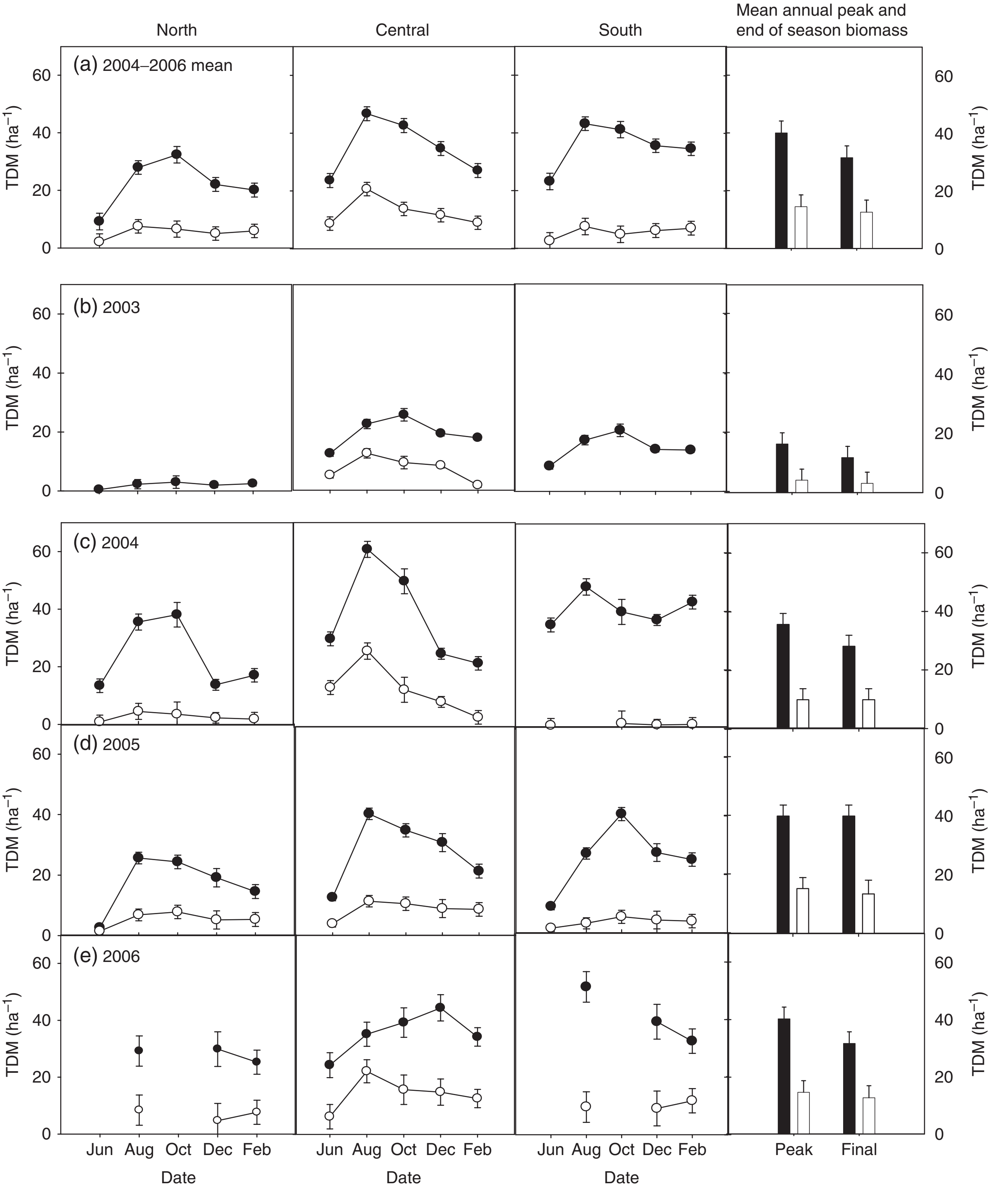

Fig. 4 Seasonal dry matter accumulation, mean peak and end of season dry biomass by Miscanthus (•) and switchgrass (○) over 4 years at locations in North, Central and Southern Illinois ($n = 4$ at each location). The year 2003 was the second year after plot establishment. Crop stands were considered mature in 2004, 2005 and 2006. TDM is equal to total plant dry mass on the date of measurement. Values are least squared means ± 1 SE.

selection for yield improvement or for ecotypes adapted to different regions. If Miscanthus yield could be improved by the 60% projected for switchgrass then the area required shrinks to 7.9 million hectares, or just 6.2% of current US cropland. This may be a far more realistic land area requirement to allow the displacement of 30% of the current US emission of 0.775 Tg CO_2 from petroleum.

Recently, Searchinger *et al*. (2008) have projected that use of both corn and perennial grasses for ethanol would result in more net carbon emissions to the atmosphere than combustion of the equivalent energy in gasoline. This results primarily from assumed indirect destruction of tropical ecosystems to obtain land for displaced food production and that any opportunity of carbon sequestration is foregone once a bioenergy crop is planted. Although the assumption of a link with tropical ecosystem destruction is not borne out by detailed assessments of causes (Geist & Lambin, 2001), the argument remains of concern. The results presented here and recently by others (Clifton-Brown *et al*., 2007; Schneckenberger & Kuzyakov, 2007) for Miscanthus, present a far more positive perspective on the benefits of perennial grasses as bioenergy feedstocks. Currently, about 18% of corn has been diverted into ethanol production in USA (RFA, 2008), projected to rise by

Table 3 Efficiencies of radiation interception and conversion in canopies of mature (3 + years old) Miscanthus and switchgrass in 2005 in Central Illinois

	Miscanthus	Switchgrass
PAR_t (MJ m^{-2})	1367	1367
ε_i	0.798	0.758
PAR_i (MJ m^{-2})	1000	967
Y (g m^{-2})	4075	1146
P (g MJ^{-1} PAR)	4.1	1.2
k (MJ kg^{-1})	18	18
ε_c	0.075	0.021

Accumulated incident photosynthetically active radiation (PAR_t) from daily met station observations, PAR interception efficiency (ε_i) from measured light interception (PAR_i), total maximum dry aboveground biomass production (Y), the conversion coefficient of radiation to biomass, the typical energy content of dry biomass (k) and the conversion efficiency of PAR (ε_c).

Table 4 The efficiencies with which switchgrass and Miscanthus turn total annual solar and photosynthetically active solar radiation into biomass

Location	Year	Crop	S_t (GJ ha^{-1} yr^{-1})	Y (GJ ha^{-1} yr^{-1})	Efficiency (total)%	Efficiency (PAR)%
North	2004	Miscanthus	51 493	685	1.33	2.96
		Switchgrass		81	0.16	0.35
	2005	Miscanthus	53 468	461	0.86	1.92
		Switchgrass		140	0.26	0.58
	2006	Miscanthus	49 720	538	1.08	2.40
		Switchgrass		152	0.31	0.68
Central	2004	Miscanthus	54 749	1095	2.00	4.44
		Switchgrass		469	0.86	1.90
	2005	Miscanthus	55 577	733	1.32	2.93
		Switchgrass		206	0.37	0.82
	2006	Miscanthus	52 146	793	1.52	3.38
		Switchgrass		396	0.76	1.69
South	2004	Miscanthus	56 401	873	1.55	3.44
		Switchgrass		35	0.06	0.14
	2005	Miscanthus	57 450	728	1.27	2.82
		Switchgrass		97	0.17	0.38
	2006	Miscanthus	55 339	924	1.67	3.71
		Switchgrass		212	0.38	0.85
Average across locations	2004	Miscanthus	54 214	884	1.63	3.62
		Switchgrass		195	0.36	0.80
	2005	Miscanthus	55 498	641	1.15	2.57
		Switchgrass		148	0.27	0.59
	2006	Miscanthus	52 045	752	1.44	3.21
		Switchgrass		253	0.49	1.08

Efficiencies were calculated using radiation data taken from nearby meteorological stations and peak biomass of each species in the respective year. Energy content of biomass assumed at 18 MJ kg^{-1} (Beale & Long, 1995).

Table 5 Biomass production, potential ethanol production and land area needed for different potential bioenergy systems to reach the 35 billion gallon US renewable fuel goal

Feedstock	Harvestable biomass ($Mg\,ha^{-1}$)	Ethanol ($gal\,ha^{-1}$)*	Million hectares needed for 35 billion gallons of ethanol	Harvested US cropland (%) in 2006†
Corn grain†	10.2	1127	31.0	24.4
Corn stover‡	7.4	741	47.2	37.2
Corn total	17.6	1868	18.7	14.8
LIHD§	3.8	380	92.1	72.5
Switchgrass	10.4	1040	33.7	26.5
Miscanthus	29.6	2960	11.8	9.3

*DOE (2006).
†USDA-NASS.
‡Perlack *et al*. (2005).
§Tilman *et al*. (2006).
LIHD, Low-input high-diversity.

Searchinger *et al*. (2008) to 43% in 2016. Here, we show that Miscanthus could provide 260% more ethanol per hectare than corn grain. The entire US renewable fuel goals for 2016 could be met today, without impacting US food production, simply by substituting Miscanthus on the land currently producing corn grain for ethanol. Miscanthus has been shown to accumulate a measured 0.5 t [C] $ha^{-1}\,yr^{-1}$ in the soil, on less productive sites than those used here (Schneckenberger & Kuzyakov, 2007). In contrast to the assumption of Searchinger *et al*. (2008), this is comparable to rates of C accumulation observed over similar periods on land entering the conservation reserve program (Gebhart *et al*., 1994).

There are technical barriers to be overcome in developing perennial grasses that are viable in large-scale energy cropping systems. However, with the efficiency and yields shown in this study, unimproved Miscanthus demonstrates the potential of a biomass feedstock to balance land use, environmental sustainability and US demand for ethanol in the near term. The higher yields per hectare shown here will increase economic return substantially and in turn the likelihood of adoption by landowners (Khanna *et al*., 2008).

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Supporting Information

The following Supporting Information for this article is available online:

Table S1. Description of locations used for trials of Miscanthus and switchgrass in Illinois. Annual temperature and precipitation are 30-year averages (Angel, 2007). Soil was sampled to 30 cm using a 5-cm-diameter core at each plot at each location ($n = 4$) in March 2003. Mineral concentrations were determined with Mehlich3 extraction (Mehlich, 1984) by the Iowa State University Plant and Soil Analysis Laboratory (Ames, IA).

Table S2. Maintenance inputs to Miscanthus and switchgrass trials established at three locations in Illinois in 2002.

Additional Supporting Information may be found in the online version of this article.

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