Title: Biomass Crops as a Source of Renewable Energy: European Experience with Miscanthus and Projections for Illinois

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Abstract

In considering renewable energy from plants, corn ethanol and reforestation have been widely promoted. Herbaceous perennials, which produce an annual crop of above ground shoots, may have important advantages over both of these systems. They require far fewer energy and financial inputs per unit biomass produced than annual arable crops. They can also be higher yielding than forestry crops and utilize existing farm equipment. They also sequester carbon into the soil, providing potential additional income in carbon credits. The advantages and disadvantages of these different plant types are explained to show why this group of plants holds special promise as biomass crops for energy on farmland. C4 plants are theoretically the most efficient type known in their conversion of sunlight energy into biomass energy. This process results not only in a higher potential efficiency of energy conversion, but also of nitrogen and water use. However, few plants in temperate climates use this more efficient process. One exception is the rhizomatous perennial grass *Miscanthus*, which is C4 and exceptionally cold tolerant. This grass is now being grown commercially in NW Europe for direct combustion in local-area power stations. It may also have longer-term potential as a feedstock for other bio-based industry. The lessons learned from trials of this crop in Europe are reported, potential yields in Illinois predicted and a tentative comparison of the economics of growing *Miscanthus* versus traditional row crops developed. Overall the results suggest that *Miscanthus* could yield an average of 14 t dry matter per acre in Illinois. At current energy prices the crop would be profitable, if grown for 12 or more years, even without subsidy.

Introduction

The carbon dioxide concentration of the atmosphere is projected to increase by almost 50% over the first 50 years of this century (IPCC 2001). The major cause of this increase is continued combustion of fossil fuels. As a result, the significant changes in climate that have already occurred will be amplified, in particular a global temperature increase. There is wide scientific consensus that if these changes continue into the second half of the century, significant damage to global ecosystems, food production and economies will ensue. The Kyoto agreement is a first attempt by the signatory countries to avert these effects. The European Union (EU) countries, which are all signatories, will meet part of this commitment to reduce net carbon dioxide emissions to the atmosphere by increasing the proportion of electricity that they generate from renewable resources. This will not only decrease their use of fossil fuels, but also their dependence on foreign energy sources. Each EU country has agreed targets. For example, the United Kingdom, which generated 1.7% of its electricity from renewable resources in 1997, is now committed to generating 10% from renewables in 2010 (European-Parliament 2001). There was initial expectation that much of this commitment would be met by wind energy. Despite the environmental benefits of this source, serious objections on the basis that wind turbines degrade the appearance of the landscape have slowed wind farm development and caused a rethink in policy. A further issue with wind is the unpredictability of the supply (Sims 2001). Far more acceptable has been the notion that rather than paying landowners to either grow or not grow food crops that are currently in surplus, incentive should be provided to grow biomass that may be used for energy generation. Unlike wind or energy, which depends on weather, biomass represents stored energy that may be drawn upon on demand. Whilst initially it was assumed that biomass crops would be of most interest for land marginal to food crop production (Paine et al. 1996), it has now been shown that it can be just as profitable to grow *Miscanthus* as wheat on some of the most highly productive land in the east of England (Bullard 2001). Such systems must have a highly favorable energy balance, i.e. low energy input versus output, since energy input usually represents a use of fossil fuel and emission of carbon to the atmosphere. Cultivation, harvest and especially nitrogen fertilization, represent large uses of fossil fuel. This has driven a shift from annuals to perennials, primarily short-rotation coppice poplars and willows, and perennial grasses, in particular *Phalaris*, *Miscanthus* and switchgrass (Venendaal et al. 1997). In contrast to annual crops, these perennials require only one cultivation activity, i.e. preparation for planting, over a 10- to 20-year duration, and minimal nitrogen inputs. As the harvested material of the plant is used for direct combustion, energy use in processing is also minimal. Thus, energy input to output in these systems may be <0.2 (McLaughlin and Walsh 1998). This contrasts sharply to corn ethanol or biodiesel from canola, where input to output is ≥ 0.8 (McLaughlin and Walsh 1998; Ulgiati 2001).

Why not simply grow and burn existing crops such as corn or wheat?

Existing food crops have a number of disadvantages as energy crops. Most are annual, requiring large inputs of energy in cultivation and planting each year (Hulsbergen et al. 2001). Much of the increase in yields that have been achieved over the past 50 years have resulted from improved partitioning of total biomass into grain and increased ability to respond to added nitrogen. Since the entire aboveground portion of the plant is used for combustion, partitioning is of little relevance for an energy crop. As noted above, a key consideration in fuel crop systems is their "energy balance"(energy in : energy out). Nitrogen fertilizers require large inputs of energy in their production. 33.5 million Btus of natural gas are needed to make 1 ton of anhydrous ammonia (Francl 2001) and further energy is spent in frequent application. Moreover, a high nitrogen content in the harvested biomass is undesirable because of its implications for pollution when combusted.

What qualities should be required of an "ideal" fuel crop?

In summary, an ideal fuel crop should have a sustained capacity to capture and convert the available solar energy into harvestable biomass with maximal efficiency and with minimal inputs and environmental impacts. The broader properties of an “ideal” fuel crop are:

Maximum efficiency of light use

The economic yields and energy efficiency of fuel crops will be determined predominantly by the amount of biomass that can be formed per unit area and per unit of investment of other resources, notably nitrogen. The potential limit on biomass yield will be set by the amount of light available, its efficiency of interception and the efficiency with which intercepted light is converted into biomass:

$$P_n = S_{tot}.\varepsilon_i.\varepsilon_c.10^3/k_b \text{ .... (1)}$$

Where, for a given time interval (e.g. 1 day) P_n is the net primary production (g m^{-1} d^{-1}), S_{tot} is incident solar radiation (MJ d^{-1}); e_i the proportion of incident radiation which is absorbed by the crop canopy (MJ/MJ); e_c the efficiency of transduction of absorbed radiant energy into chemical energy, in the form of plant biomass (MJ/MJ); and k_b the energy content of the biomass (MJ kg^{-1}). Interception efficiency depends on the duration, size and architecture of the canopy. A crop that can maintain a closed canopy throughout the year, or at least through the period of maximum insolation (i.e. March - October), will clearly have the highest e_i. In temperate regions the major factor determining e_i is ability to develop leaves rapidly at the start of the growing season. The complete canopy cover needed to maximize e_i also minimizes the availability of light to weeds, so minimizing herbicide requirements.

Water content and water use efficiency

Ideally, the harvested biomass should be dry. Wet biomass will either require an input of energy for drying or if combusted will decrease the efficiency of sensible heat production. This conflicts with the need to maximize interception efficiency for photosynthesis. However a compromise would be for the shoots to die annually and dry-down in the winter, when the available solar radiation is small and decreased interception efficiency will be of least importance. Herbaceous perennials forming an annual crop of stems have just such a growth cycle, thus maximizing e_i during the growing season, while minimizing water content in the harvested fuel. Water use efficiency is another important criterion in selecting fuel crops. Available soil water is a significant limitation to crop production over much of N. America and Europe, and irrigation requires significant inputs of energy whilst placing a demand on diminishing water resources.

Nitrogen and nutrient use efficiency

Nitrogen use efficiency is determined at three levels. First, by maximizing the efficiency of energy transduction into biomass in photosynthesis per unit of nitrogen invested in the photosynthetic apparatus. Secondly, by maximizing the amount of N, and other nutrients, translocated out of the canopy components on their senescence, either into other leaves or storage organs; i.e. efficient internal recycling. Thirdly, by maximizing capture of nutrients from the soil. This property will help to minimize both the quantities of N that need to be applied as fertilizer and the amount lost to drainage water.

Cultivation, and disease and pest control

Cultivation operations including ploughing, planting, and chemical applications all constitute energy inputs; fuel crops need therefore to have a form and life cycle that would minimize the need for these operations. Energy efficiency and environmental acceptability will be helped by selecting crops with a minimum need for pesticide, fungicide and herbicide applications. Selecting non-food crop species and maintaining genetic diversity is likely to minimize pest and disease losses. Selection of plants that occur naturally in monotypic stands may also be advantageous. Only species which lack major diseases and pests could occur naturally in such stands.

Minimizing changes in land use and farm machinery

Finally, energy crop acceptability will be greatest and costs of conversion least, if the plants selected as fuel crops can be i) planted and harvested with the machinery used for food crops; ii) easily eradicated should the landowner subsequently want to change land use, and iii) provide harvestable material in a short period of time.

Environmental impacts and benefits

Highly productive species may often be invasive and able to out-compete native species. A particular challenge is in selecting highly productive germplasm that cannot spread into the adjacent natural communities. In addition, some energy crops would have added environmental benefits over current food crops. Perennials providing above ground structures throughout the year may provide wildlife refuges. Production and turnover of belowground storage organs will add organic matter and carbon to the soil. Perennials have more extensive root systems present throughout the year, so providing increased resistance to soil erosion and a more effective means of trapping nutrients and preventing nitrogen loss to drainage water. Because the crop is not used for food, the land could also be suitable for spreading sewage sludge and farm effluents that may represent health risks in areas sown with food crops.

End uses

While the expectation is that these crops would be sold as biomass for combustion, alternative markets will be important for maintaining price stability. The ideal crop would therefore provide biomass suitable as a feedstock for a range of biobased industrial processes – such as paper production, biocomposites, and fermentation.

C_4 rhizomatous, perennial grasses. The ideal energy crop?

C_4 photosynthesis is the most efficient known, with the highest potential for converting sunlight energy into biomass energy. This group also has the highest efficiencies of nitrogen and water use. C_4 crops in N. America and Europe include maize and sorghum. Both of these crops, however, have serious shortcomings with regard to other specifications (Table 1). As improved annual crops, both have considerable cultivation and pesticide application requirements. They also have a relatively short canopy duration leading to a poor interception of available sunlight in the early growing season and in the early fall. As annuals, they are unable to recycle nutrients from one year's growth to the next and at the beginning of the growing season their small, undeveloped root systems preclude efficient capture of nutrients, leading to losses of applied fertilizer. Trees and shrubs might provide an obvious alternative as fuel crops since wood provides a high-density fuel. However, there are drawbacks (Table 1). No temperate trees are C_4, wood at harvest can contain large quantities of water, several years are required between planting and harvest, and once planted the land occupied cannot be easily converted back to arable use. The wood is also a store of nutrients, making it polluting on combustion and resulting in nutrient off-take from the soil. Some herbaceous rhizomatous perennials, i.e. perennial plants that produce an annual crop of shoots that die back in the winter, lack these drawbacks. These plants maintain a large root system providing efficient capture of nutrients, but can also translocate nutrients from the annual shoots to the perennating below-ground organs (rhizomes) as winter approaches. The dead shoots can then provide low mineral, dry standing biomass, which may be harvested with conventional forage/herbage harvesters. As perennials, they require only initial cultivation and planting. In contrast to trees they may be easily removed with glyphosate and tillage to convert the land back to arable agriculture. Two groups of C_4 rhizomatous, perennial grasses have been identified as potential biomass crops in Europe and N. America – switchgrass (*Panicum virgatum*) and *Miscanthus* (*Miscanthus* spp.).

Limitations of herbaceous C_4 perennials

Though in theory this group of plants comes the closest to the specified ideal for fuel crops (Table 1), they have disadvantages in practice when cultivated in the cool temperate climates of the upper 48 states, S. Canada and N. Europe. Whilst there are a wide range of C_4 herbaceous perennials, the vast majority are tropical in origin, and in common with most plants of tropical origin, show a high temperature threshold for leaf growth and a susceptibility to low temperature dependent photoinhibition of photosynthesis. *Miscanthus,* however, appears exceptional. It develops its canopy early, even at 52°N and forms photosynthetically competent leaves at 10°C. At 52°N it can yield over 8 t DM acre^{-1} yr^{-1}, yet show the high N-use and water-use efficiency characteristic of C_4 plants at warmer temperatures (Beale and Long 1997; Beale et al. 1999). It has also been shown to accumulate organic matter in the soil at a rate of about 4 t acre^{-1} yr^{-1} (Beuch et al. 2000; Kahle et al. 2001).

Table 1

Characteristics of the ideal biomass energy crop.	Corn	Short-rotation coppice	Miscanthus
C_4 photosynthesis	+		+
Long canopy duration		+	+
Perennial (no need for annual tillage or planting)		+	+
No known pests or diseases			+
Rapid growth in spring to out compete weeds		+	+
Sterile prevent “escape”	n/a		+
Stores carbon in soil (soil restoration and carbon sequestration tool)		+	+
Recycles nutrients back to roots in fall (low fertilizer requirement).			+
Low nutrient content (very clean burning)			+
High water use efficiency			+
Dry down in field (zero drying costs)	?		+
Good winter standing (harvest when needed; zero storage costs)		+	+
Utilizes existing farm equipment	+		+
Alternative markets (high quality paper, building materials, and fermentation)	+	+	+

Miscanthus, an Introduction

Above we explain why *Miscanthus* appears, in theory, particularly suitable as a biofuel crop for temperate areas, in the context of providing dry biomass for combustion in energy generation. Below we outline the experience with this crop in Europe and the potential of the crop in Illinois and the US in general.

What is *Miscanthus*?

The genus *Miscanthus* originates in the tropical/subtropical regions of Southeast Asia. It is found over a wide range, both spatially and climatically, from the Pacific Islands to the mountains of Japan (Greef and Deuter 1993). The species most commonly investigated as a biofuel in the EU, *M.* x *giganteus,* is a naturally occurring sterile triploid hybrid (2n=57) with parents *M. sacchariflorus and M. sinensis* (Greef et al. 1997; Hodkinson et al. 2002b). In 1935, a sample of *M.* x *giganteus* was collected in Yokohama, Japan and subsequently planted in Denmark, and found to retain productivity even in that cool climate (Lewandowski et al. 2000; Linde Laursen 1993). Based on this observation of vigorous growth, *M.* x *giganteus* was proposed as a biofuel in Europe, and extensive field trials have been performed there since 1983 (Lewandowski et al. 2000). Since this time, other *Miscanthus* species have been identified with some traits desirable over those of *M.* x *giganteus*, thus indicating the large genetic diversity of this genus will be an asset in breeding new lines of *Miscanthus* for energy production (Clifton-Brown and Lewandowski 2002; Greef et al. 1997).

Experience in Europe

Renewable energy production has a central role to play in abating net CO_2 emissions to a level that will arrest the development of global warming. The European Union has committed to double, from 6% to 12%, their energy supply from renewable sources by the year 2010(Anonymous 1997). Under the Kyoto protocol there is a European target of 8% reduction in CO_2 emissions from 1990 levels, towards which CO_2-neutral energy crops could make a large contribution. In addition, perennial energy crops can help to ensure sustainable land use and increase rural employment as well as improving energy security through indigenous fuel supply.

In northern Europe the most enthusiastically promoted energy crops have been willow and poplar short rotation coppice, but this is now closely followed by *Miscanthus* and other perennial, rhizomatous grasses. These grasses also have other potential uses that have been tested on a pilot scale, which are either additional or alternative to energy production (Visser and Pignatelli 2001).

Experience in developing *Miscanthus* as an energy crop in Europe has been reviewed previously (Jones and Walsh 2001; Lewandowski et al. 2000). Here the potential advantages and disadvantages of growing this crop have been discussed. They have also provided a general overview of research and development priorities for *Miscanthus*. From the experience gained from *Miscanthus* in Europe it is now possible to draw conclusions for the transfer application of *Miscanthus* cultivation for energy production in North America. A ‘supply chain analysis’ can now be performed to identify the main bottle necks which will need to be over come before the cultivation and use of *Miscanthus* becomes economically viable in N. America.

Selection of cultivars

The majority of trials in Europe have involved clones of one *Miscanthus* species, *M.* x *giganteus*, although other genotypes have also been evaluated (Greef and Deuter 1993; Hodkinson and Renvoize 2001). In northern cooler regions *M. sinensis* appears to be better adapted than *M.* x *giganteus*. A general observation in the selection of cultivars has been the fact that *M. sacchariflorus* makes a contribution to the genome to allow for warmer climates while *M. sinensis* provides genetic resources for cooler regions. Crosses between tetraploid *M. sacchariflorus* and diploid *M. sinensis* result in triploid hybrids which can have vigorous growth and certain stress tolerance characteristics, but cannot produce viable seed, and hence pose no risk as a weed.

Establishment

The first step in the supply chain analysis is crop establishment. Since *M. x giganteus* is sterile, it must be propagated vegetatively, either from rhizome cuttings or micro-propagation. Most trials in Europe have used young plants that are transplanted directly into freshly cultivated soil at a density of 2-3 plants m^{-2} after the risk of the last spring frost has passed. Another option is to plant dormant, winter-state rhizomes into cultivated soil in early spring. The full establishment of a *Miscanthus* stand takes from 2 to 5 years depending on the climatic conditions. Typically, a ceiling yield is reached in 2 years in southern Europe and up to 5 years in Northern Europe.

Cultural Practices

In most areas, plants benefit from irrigation for the first month after planting. In Northern Europe there appears to be some risk of loss of newly established stands due to low winter temperatures (Clifton-Brown J C and Lewandowski 2000; Jorgensen and Schwarz 2000). Weed control is essential in the first two years during the period from plant emergence to canopy closure. It has been the European experience that unless soils are very nutrient poor, fertilizers are not needed in the first 2 years. In the 3^{rd} and subsequent years, fertilizer applications are typically 40-100 N, 10-20 P and 40-100 kg K ha^{-1} depending upon the nutrient off-take at harvest. Precise fertilizer off-takes are dependent both on the yield and time of harvest, the latter due to increased translocation of nutrients below ground as the crop dries down in the field. These requirements far exceed theoretical expectation and show lower efficiencies than in other rhizomatous perennials, suggesting a major area where breeding is needed to improve *Miscanthus* (Beale and Long 1997).

Yield Potential

Fully established plants grow 3-4 m tall stems and foliage by the end of the growing season and yield from 10 to 40 t DM ha^{-1} y^{-1} depending on local agronomic conditions. The length of the growing season is constrained by the time of the latest frost in spring and the occurrence of the first frost in autumn (Clifton-Brown et al. 2000). Predictions of the production potential throughout Europe have been made for *M. x giganteus*, based on local climatic conditions (temperature, radiation, rainfall and soil water holding capacity), using a model called *MiscanMod* (Clifton-Brown et al. 2002) Research trials have validated model estimates and suggest *MiscanMod* is applicable over a wide climatic range in Europe (Clifton-Brown et al. 2002). Key areas for successful rainfed production of *M. x giganteus* include the lowland areas surrounding the Alps where autumn yields are typically higher than 25 t DM ha^{-1}. The warm and moist summer climate of this area may be the closest, climatically, to the Midwest.

Harvesting

Harvesting does not commence until the crop has fully senesced because earlier harvesting would result in high nutrient off-takes and plant biomass with a high moisture content. There is a play-off between the quantity and the quality of harvested biomass in relation to harvest time. Winter losses of dead and decaying leaves and upper stem parts can cause yield reductions from 30 to 50% dry matter (Jorgensen 1997), but field drying reduces both the mineral and water content of the crop, allowing for a cleaner fuel and retention of more nutrients in the field. Harvesting can be carried out using existing farm machinery, thus avoiding heavy investment in specialized equipment. Corn silage choppers appear to be the most suitable forms of machinery that are currently available. However, bailers following mowers are also commonly used.

Combustion

Combustion characteristics of *Miscanthus* are favorable compared to wheat straw. A drawback to combustion of *Miscanthus* is the low ash melting point of the biomass, which can be problematic in some boiler systems. This trait may be due to relatively high silica and potassium contents in the harvested crop (Lewandowski and Kicherer 1997). *Miscanthus* has been successfully burned on a commercial scale in Denmark using a 78 MW circulating fluidized-bed combustor (50% co-firing with coal) and 160 MW powered fuel combustor (20% co-firing).

Potential

Using the empirical yield model of (Clifton-Brown et al. 2000), we can predict that if 10% of the land area currently used in the EU for rainfed arable and agricultural grassland was planted with Miscanthus 425 TWh of electricity could be generated. This is 17% of the EU's current annual consumption of 2530 TWh (European-Parliament 2001). This figure assumes no use of marginal lands and no improvement of the crop, which are both likely to improve the potential of the crop.

Projections for Illinois

(Clifton-Brown et al. 2000), using yield data for *Miscanthus* across the European Union developed an agro-climatic model for predicting yields. We have now applied this model to several sites in Illinois (Fig. 1). A mean yield of 14 t DM acre^{-1} across the state is suggested, with yields ranging from 11 – 18 t DM acre^{-1}. Studies in Europe suggest that maximum yield is achieved by about year 3 and then maintained for many years following establishment.

TABLE 2. Annual and **10-year** projected costs and profits for two systems in Central Illinois

	Corn/Soybean[1] rotation			Miscanthus[2] energy crop			
$/acre	*Corn*	*Soy*	**10 years**	*1st year*	*2nd year*	*3rd-10th*	**10 years**
Fertilizer	53	19	**360**	25	10	10	**115**
Pesticides	31	32	**315**	5	0	0	**5**
Seed	34	19	**265**	128	0	0	**128**
Crop Drying	7	2	**45**	0	0	0	**0**
Machinery repair, fuel, hire	27	24	**255**	13	20	20	**193**
TOTAL VARIABLE	152	96	**1240**	171	30	30	**441**
Labor	36	34	**350**	60	3	3	**87**
Building, storage	17	9	**130**	4	2	2	**22**
Machinery, depreciation, non-land interest, overhead	87	71	**790**	43	20	20	**223**
TOTAL OTHER	140	114	**1270**	107	25	25	**332**
LAND COST	151	151	**1510**	151	151	151	**1510**
TOTAL ALL COSTS	443	361	**4020**	429	206	206	**2283**
Yield, Bu/acre	*166*	*52*					
Yield, Dry tons/acre				*0*	*7*	*14*	
Value $/Bu	*2.50*	*5.30*					
Value $/ton					*30*	*30*	
INCOME FROM CROP $/acre	415	275.6	**3453**	0	210	420	**3570**
NET PROFIT (farm gate excluding subsidies) $/acre	-28	-85.4	**-567**	-429	4	214	**1287**

[1] Corn and Soybean costs and average yields for Central Illinois after Hoeft RG, Nafziger ED, Johnson RR, Aldrich SR (2000) Modern Corn and Soybean Production. MCSP Publications, Champaign, IL and prices based on Chicago Board of Trade Dec. 2002 futures.
[2] Miscanthus seed and planting costs based on Lewandowski I, Clifton-Brown JC, Scurlock JMO, Huisman W (2000) Miscanthus: European experience with a novel energy crop. Biomass & Bioenergy 19:209-227 and harvest costs assuming cutting and baling as for corn silage. A predicted yield of 14 t/ac for Central IL is assumed (Fig. 1), and a price of $30 /t. This compares to$ 40 /t offered by Dynegy for co-combustion with coal and an EU suggested price of $49 /t Bullard M (2001) Economics of Miscanthus Production. In: Jones MB, Walsh M (eds) Miscanthus for Energy and Fibre. James & James, London, p 155-171

In general, there is insufficient yield in year 1 to merit a harvest and yields in year 2 are at least 50% of those achieved in the subsequent years (Clifton-Brown et al. 2001b). Given this potential performance, how do the economics of this system compare to the corn/soy system, which covers much of the Midwest? Table 2 shows that even without subsidies this system appears profitable, unlike the traditional corn/soy rotation, which depends heavily on government support. Most of the expense of a *Miscanthus* stand is in planting, not maintenance, and with profits from the crop in subsequent years, the crop will be highly profitable if maintained for 10 years (Table 2). This assumes a crop value of $30 per ton, though this modest value is below current projections. The minimum value of *Miscanthus* would be $17/ton, based on calorific value relative to bituminous coal ($38/ton). At this bottom rate, the crop would only be profitable if maintained for a minimum of 12 years.

Future needs in developing grass-based energy biomass crops

Using perennial, rhizomatous grasses as a source of renewable energy is a relatively new concept, with much room for improvement. Energy crop research is a nascent field in comparison with that of current food crops, some of which may have been selected over thousands of years of cultivation. Opportunities for improvement exist throughout the supply chain, from crop genetics to cultivation and transport technology, and finally to end product utilization by power stations.

Genetic screening and improvement

As mentioned above, the risk of escape is often a concern when a new species is introduced to an area, and therefore sterility should be viewed as a desirable trait in an energy crop. Although this limits crop improvement through traditional crop breeding, different variants of *M. x giganteus* can still be created by crossing the parents species to create new triploid hybrids (Jorgensen and Muhs 2001). However, genotypic and phenotypic variation already exists in the sterile triploid hybrid *M. x giganteus*, (Greef et al. 1997; Hodkinson et al. 2002a). This variation can be exploited to optimize biomass production in different areas of the world. Regional environmental and climatic factors can dramatically affect both crop yield and fuel quality, thus providing the opportunity to screen existing *M. x giganteus* genotypes and select those which perform best in a given region (Clifton-Brown and Lewandowski 2002; Clifton-Brown et al. 2001a). Switchgrass, another perennial, rhizomatous grass used for energy production, does produce fertile seed, and the biofuel characteristics of the plant can be improved through traditional breeding efforts (Hopkins et al. 1995). Even so, the climatic range of high yielding switchgrass production will likely be limited to lower latitudes (Madakadze et al. 1998; Madakadze et al. 1999).

Cultural Practices

As described above, cultivation and management techniques can also impact both yield and quality of energy crops. Fertilization, harvest time, harvest method and cutting height are just some of the factors that can influence biomass production (Jorgensen and Sander 1997). For example, there is a trade off between maximum yield and minimum moisture content in *Miscanthus* as the crop dries down in the field (El Bassam and Huisman 2001). Switchgrass, by comparison, does not stand well in the field after senescence, and is usually harvested in the fall to reduce lodging losses, and dried mechanically if necessary. Used in tandem, a crop system of switchgrass and *Miscanthus* could provide a year round energy supply. Switchgrass could be harvested and used during the summer months and *Miscanthus* allowed to stand and dry for winter use. Fertilization can also affect crop and fuel quality. Levels of ash, chlorine and potassium, all of which are undesirable byproducts of combustion, can rise with increasing potassium fertilization (Lewandowski and Kicherer 1997). In depth evaluation such factors, as well as their interactions, will be necessary to refine cultural practices to both maximize yield and optimize fuel quality.

Technology

Given the novelty of energy crop production, it is reasonable to expect large gains in efficiency early on due to technological improvements. Energy crop production has yet to be mechanized in the same way as food crop production, though the jump in technology is likely a small one. Equipment that is currently used for food crops can be used for energy crops, and minor modifications of this equipment will help to streamline energy crop adoption by agricultural producers (Bullard 1996; Huisman et al. 1997). Potato planters or manure spreaders can both be used to plant *Miscanthus* rhizomes, but adaptations of these implements, as well as the development of precision planting systems can provide significantly superior establishment (Nixon et al. 2001). Traditional forage harvesters are used to harvest both *Miscanthus* and switchgrass but yield losses and harvest costs can increase with repeated handling of the crop (Huisman et al. 1997). After cutting, the crop must then be parceled in a form suitable for transportation and then processed to be useable by the power station. Combined mowing and baling, or the consolidation of more steps (e.g. a machine that could harvest and pelletize in the field) would reduce time and labor expenses as well as loss of harvested material (El Bassam and Huisman 2001). Processing of the biomass from crop into fuel is another point in the supply chain at which efficiency may be gained. The end use of the fuel will determine it's final form, e.g. shredded bales of biomass for straight combustion, pellets made from biomass and industrial binding agents for co-firing with coal, or even slurry for alcohol fermentation.

Conclusion

The concept of crops grown specifically for energy has developed rapidly in the past few decades. Herbaceous, rhizomatous perennials such as *Miscanthus* and switchgrass have been found to possess numerous advantages over annual food crops and woody short rotation coppice species, lending them for consideration as "ideal" energy crops. *Miscanthus* has proven productive under a wide array of climatic conditions in the EU, even at latitudes normally prohibitive to C4 species. At expected levels of production and crop value in central Illinois, economic analysis of *Miscanthus* production systems compares favorably to a corn/soy rotation in the long term, even without consideration of subsidy or remuneration for the ecosystem services *Miscanthus* provides. Models based on the EU experience predict *Miscanthus* yields in Illinois could be nearly twice those achieved in Europe. Nonetheless, improvements can be made at every step of the supply chain, and it is reasonable to expect large gains in efficiency and concomitant reductions in cost as easily implemented modifications made to the current system begin to streamline commercial production.

References.

Anonymous (1997) Renewable energy: White Paper laying down a Community Strategy and action plan. European Commission

Beale CV, Long SP (1997) Seasonal dynamics of nutrient accumulation and partitioning in the perennial C-4-grasses Miscanthus X giganteus and Spartina cynosuroides. Biomass and Bioenergy 12:419-428

Beale CV, Morison JI, Long SP (1999) Water use efficiency of C4 perennial grasses in a temperate climate. Agricultural and Forest Meteorology 96:103-115

Beuch S, Boelcke B, Belau L (2000) Effect of the organic residues of Miscanthus X giganteus on the soil organic matter level of arable soils. Journal of Agronomy and Crop Science 184:111-119

Bullard M (2001) Economics of Miscanthus Production. In: Jones MB, Walsh M (eds) Miscanthus for Energy and Fibre. James & James, London, p 155-171

Bullard MJ (1996) Planting and harvesting Miscanthus giganteus. Landwards 51(2):17-19

Clifton-Brown J C, Lewandowski I (2000) Overwintering problems of newly established Miscanthus plantations can be overcome by identifying genotypes with improved rhizome cold tolerance. New Phytologist 148:287-294

Clifton-Brown JC, Lewandowski I (2002) Screening Miscanthus genotypes in field trials to optimise biomass yield and quality in Southern Germany. European Journal of Agronomy 16:97-110

Clifton-Brown JC, Lewandowski I, Andersson B, Basch G, Christian DG, Kjeldsen JB, Jorgensen U, Mortensen JV, Riche AB, Schwarz KU, Tayebi K, Teixeira F (2001a) Performance of 15 Miscanthus genotypes at five sites in Europe. Agronomy Journal 93:1013-1019

Clifton-Brown JC, Lewandowski I, Stampfl P, Jones MB (2002) Modelled biomass production potential of Miscanthus and actual harvestable yield as influenced by harvest time 12 th European Biomass Conference and Exhibition, Amsterdam

Clifton-Brown JC, Long SP, Jorgensen U (2001b) Miscanthus Productivity. In: Jones MB, Walsh M (eds) Miscanthus for Energy and Fibre. James & James, London, p 46-67

Clifton-Brown JC, Neilson B, Lewandowski I, Jones MB (2000) The modelled productivity of Miscanthus x giganteus (GREEF et DEU) in Ireland. Industrial Crops and Products 12:97-109

El Bassam n, Huisman W (2001) harvesting and storage of Miscanthus. In: Jones MB, walsh m (eds) Miscanthus for energy and fibre. james and james, ltd, london

European-Parliament (2001) Directive 2001/77/EC of the European Parliament and of the Council of 27 September 2001 on the promotion of electricity produced for renewable energy sources in the internal electricity market. Official Journal of the European Communities:27.10.2001, L 283/33

Francl T (2001) High natural gas prices are choking nitrogen fertilizer production. American Farm Bureau Federation

Greef JM, Deuter M (1993) Syntaxonomy of Miscanthus times giganteus GREEF et DEU. Angewandte Botanik 67:87-90

Greef JM, Deuter M, Jung C, Schondelmaier J (1997) Genetic diversity of European Miscanthus species revealed by AFLP fingerprinting. Genetic Resources and Crop Evolution 44:185-195

Hodkinson TR, Chase MW, Renvoize SA (2002a) Characterization of a genetic resource collection for *Miscanthus* (Saccharinae, Andropogoneae, Poaceae) using AFLP and ISSR PCR. Annals of Botany 89:627-636

Hodkinson TR, Chase MW, takahashi c, leitch i, bennett m, Renvoize SA (2002b) The use of DNA sequencing (ITS and *TRNL-F*), AFLP and fluorescent in situ hybridization to study allopolyploid *Miscanthus* (Poaceae). American journal of botany 89:279-286

Hodkinson TR, Renvoize SA (2001) Nomenclature of Miscanthus x giganteus (Poaceae). Kew Bulletin 56:759-760

Hoeft RG, Nafziger ED, Johnson RR, Aldrich SR (2000) Modern Corn and Soybean Production. MCSP Publications, Champaign, IL

Hopkins AA, Vogel KP, Moore KJ, Johnson KD, Carlson IT (1995) Genotype effects and genotype by environment interactions for traits of elite switchgrass populations. Crop sci 35:125-132

Huisman W, Venturi P, Molenaar J (1997) Costs of supply chains of Miscanthus giganteus. Ind crop prod New York : Elsevier, 1992-. Aug 1997. v. 6:p

Hulsbergen KJ, Feil B, Biermann S, Rathke GW, Kalk WD, Diepenbrock W (2001) A method of energy balancing in crop production and its application in a long-term fertilizer trial. Agriculture Ecosystems & Environment 86:303-321

IPCC (2001) Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge

Jones MB, Walsh M (2001) Miscanthus for Energy and Fibre. James and James Ltd., London

Jorgensen U (1997) Genotypic variation in dry matter accumulation and content of N, K and Cl in Miscanthus in Denmark. Biomass and Bioenergy 12:155-169

Jorgensen U, Muhs H-J (2001) Miscanthus Breeding and Improvement. In: Jones MB, walsh m (eds) Miscanthus for energy and fibre. james and james, ltd., london

Jorgensen U, Sander B (1997) Biomass requirements for power production: How to optimise the quality by agricultural management. Biomass and Bioenergy 12:145-147

Jorgensen U, Schwarz KU (2000) Why do basic research? A lesson from commercial exploitation of miscanthus. New Phytologist 148:190-193

Kahle P, Beuch S, Boelcke B, Leinweber P, schulten HR (2001) Cropping of Miscanthus in Central Europe: biomass and influence on nutrients and soil organic matter. European Journal of Agronomy 15:171-194

Lewandowski I, Clifton-Brown JC, Scurlock JMO, Huisman W (2000) Miscanthus: European experience with a novel energy crop. Biomass & Bioenergy 19:209-227

Lewandowski I, Kicherer A (1997) Combustion quality of biomass: Practical relevance and experiments to modify the biomass quality of Miscanthus x giganteus. European Journal of Agronomy 6:163-177

Linde Laursen I (1993) Cytogenetic analysis of Miscanthus 'Giganteus', an interspecific hybrid. Hereditas 119:297-300

Madakadze IC, Coulman BE, McElroy AR, Stewart KA, Smith DL (1998) Evaluation of selected warm-season grasses for biomass production in areas with a short growing season. Bioresource Technology 65:1-12

Madakadze IC, Stewart K, Peterson PR, Coulman BE, Smith DL (1999) Switchgrass biomass and chemical composition for biofuel in eastern Canada. Agronomy Journal 91:696-701

McLaughlin SB, Walsh ME (1998) Evaluating environmental consequences of producing herbaceous crops for bioenergy. Biomass & Bioenergy 14:317-324

Nixon PMI, Boocock H, Bullard MJ (2001) An evaluation of planting options for Miscanthus. In: Bullard MJ, Christian DG, Knight JD, Lainsbury MA, Parker SR (eds) Biomass and Energy Crops II 65

Paine LK, Peterson TL, Undersander DJ, Rineer KC, Bartelt GA, Temple SA, Sample DW, Klemme RM (1996) Some ecological and socio-economic considerations for biomass energy crop production. Biomass & Bioenergy 10:231-242

Sims REH (2001) Bioenergy opportunities for climate change mitigation. In: Bullard MJ, Christian DG, Knight JD, Lainsbury MA, Parker SR (eds) Biomass and Energy Crops II. The Association of Applied Biologists, York 65

Ulgiati S (2001) A comprehensive energy and economic assessment of biofuels: When "green" is not enough. Critical Reviews in Plant Sciences 20:71-106

Venendaal R, Jorgensen U, Foster CA (1997) European energy crops: a synthesis. Biomass & Bioenergy 13:147-185

Visser P, Pignatelli V (2001) Utilisation of Miscanthus. In: Jones MB, walsh m (eds) Miscanthus for Fibre and Energy. James and James, ltd., London