

ORNL/TM-13732

Environmental Sciences Division

**Miscanthus:
A Review of European Experience
with a Novel Energy Crop**

J. M. O. Scurlock
Environmental Sciences Division
Oak Ridge National Laboratory
P.O. Box 2008
Oak Ridge, TN 37831-6407
U.S.A.

Environmental Sciences Division
Publication No. 4845

Date Published: February 1999

Prepared for the
U.S. DEPARTMENT OF ENERGY
Office of Transportation Technologies and Office of Power Technologies
Budget and Reporting Nos. EB 52 03 00 0 and EB 24 04 00 0

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831-6422
managed by
LOCKHEED MARTIN ENERGY RESEARCH CORP.
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-96OR22464

CONTENTS

	Page
FIGURES	v
TABLES	vii
ABSTRACT	ix
1. INTRODUCTION	1
2. VARIETIES EVALUATED IN EUROPE	1
3. TEST LOCATIONS, SIZES, AND DURATIONS	3
4. CROP PHYSIOLOGY	5
5. CULTURAL PRACTICES EMPLOYED	5
6. ENERGY AND CO ₂ BALANCE: OTHER ENVIRONMENTAL CONSIDERATIONS	7
7. ECONOMICS	8
8. COMBUSTION CHARACTERISTICS	8
9. CONCLUSIONS AND SUMMARY	9
10. CONTACTS FOR FURTHER INFORMATION	11
11. REFERENCES	12

FIGURES

	Page
1. Mature stand of <i>Miscanthus x giganteus</i>	2
2. Demonstration plot of <i>Miscanthus x giganteus</i> pictured just before harvest	2
3. Miscanthus rhizome propagation material ready for planting (length is about 10 cm)	5
4. Harvesting of demonstration plot of <i>Miscanthus x giganteus</i> using a <i>Kemper Champion 4500</i> forage harvester mounted on a <i>John Deere</i> combine.	6
5. Baling of miscanthus straw from a demonstration plot, using a <i>Claas</i> baler	7

TABLES

	Page
1. Comparison of the properties of miscanthus and switchgrass	10

ABSTRACT

Scurlock, J. M. O. (1998). *Miscanthus*: a review of European experience with a novel energy crop. ORNL/TM-13732. Oak Ridge National Laboratory, Oak Ridge, Tennessee. 26 pp.

Miscanthus is a tall perennial grass which has been evaluated in Europe over the past 5–10 years as a new bioenergy crop. The sustained European interest in miscanthus suggests that this novel energy crop deserves serious investigation as a possible candidate biofuel crop for the United States alongside switchgrass. To date, no agronomic trials or trial results for miscanthus are known from the conterminous United States, so its performance under U.S. conditions is virtually unknown. Speculating from European data, under typical agricultural practices over large areas, an average of about 8t/ha (3t/acre dry weight) may be expected at harvest time. As with most of the new bioenergy crops, there seems to be a steep "learning curve." Establishment costs appear to be fairly high at present (a wide range is reported from different European countries), although these may be expected to fall as improved management techniques are developed.

1. INTRODUCTION

Extensive field trials of *Miscanthus x giganteus*, a sterile hybrid genotype of the large perennial grass miscanthus, have been carried out in northern Europe since 1983. The yield potential of this novel annually harvested bioenergy crop has been shown to be substantial, but some concerns remain about drawbacks, such as its relatively high establishment costs and its currently narrow genetic base.

Miscanthus was first cultivated in Europe in the 1930s, as an ornamental introduction from Japan. A number of other ornamental varieties of miscanthus are also known to exist under various common names. The yield potential of miscanthus for cellulose fiber production was investigated in the late 1960s in Denmark. Trials for bioenergy production commenced in Denmark in 1983, spreading to Germany in 1987 before more widespread evaluation throughout Europe. Possessing the efficient C₄ photosynthetic pathway (with relatively low nutrient and water requirements), yet tolerant of cool temperate climates, miscanthus is potentially an "ideal" energy crop because its annual cropping cycle provides a regular income for the grower (unlike woody crops, harvested only every 2–4 years). Lower-cost methods of establishment, together with improved overwintering, had been developed by the mid-1990s, although much research still remains to be done (Lewandowski 1998a).

The highest aboveground standing biomass is found at the end of each growing season (up to 20–30 t/ha dry weight), but it is usually considered desirable to allow the crop to dry out over winter, with losses of 30–50% of the standing biomass (Figs. 1 and 2). Such losses are tolerated because of the resulting improvements in fuel quality. Moisture content may drop to as low as 15% by early spring, with resultant advantages in handling and little need for further drying. Ash and mineral content are also reduced (because many nutrients are recycled through leaf drop and re-translocation to the rhizomes), alleviating the problems that elements such as potassium and chlorine may cause in biomass fuel processing. The final annual yield at harvest is therefore up to 12–18 t/ha (dry weight), although large-scale semicommercial trials suggest about 7–9 t/ha (dry weight) is a more reasonable estimate over large areas. Rotations are estimated to be from 15 to 25 years, although most older trial stands are only in their 6th to 8th year of cropping, and few European stands can be more than 10 years old.

2. VARIETIES EVALUATED IN EUROPE

Most European trials have involved clones of *M. x giganteus*, a triploid hybrid ($n = 57$) of uncertain origin, probably *M. sinensis* (diploid) x *M. sacchariflorus* (tetraploid). This was introduced into Denmark in 1935 from Yokohama, Japan, although the genus is known to occur throughout tropical, subtropical, and warm temperate parts of South-East Asia (where it probably has its origin) and the Pacific Islands. A member of the *Andropogoneae/Poaceae* family, the genus is closely related to *Saccharum* (which includes sugar cane), and some species of the two genera are easily intercrossed. In general, *M. sacchariflorus* types are well adapted for warmer climates, whereas *M. sinensis* can provide genetic resources for cooler regions. The European Miscanthus Improvement (EMI) project aims to broaden the genetic base of miscanthus, maximizing the productivity and adaptive range of the crop, and to develop methods for



Figure 1. Mature stand of *Miscanthus x giganteus*. The taller man has a height of about 1.9 m, so the stand is approximately 3.5 m high. Photograph taken September 1996, about 30 km south of Ulm in southern Germany, by Dr. I. Lewandowski, University of Hohenheim. A color version of the image is on the Bioenergy Information Network website photo gallery (<http://www.esd.ornl.gov/bfdp/>).



Figure 2. Demonstration plot of *Miscanthus x giganteus* pictured just before harvest. Scale divisions on range poles are 0.5 m, so stand is about 2.5 m tall. Photograph taken February 1995, Forchheim, Baden-Württemberg, southern Germany, by Dr. I. Lewandowski, Institute for Crop Production and Grassland Research, University of Hohenheim, Germany. Reproduced by permission. A color version of the image is on the Bioenergy Information Network website photo gallery (<http://www.esd.ornl.gov/bfdp/>).

achieving these objectives. In 1997, extensive trials began of 15 genotypes across 5 different locations in Europe, from Sweden to Portugal (Lewandowski 1998a). Results to date from widespread trials suggest that yields of up to 25 t/ha/year (dry weight) may be obtained at the time of harvest (typically February), under conditions from central Germany (lat. 50° N) to southern Italy (lat. 37° N). More southerly locations, where water is usually a limiting factor in crop production, have employed irrigation. Yields in more northern parts of Europe (lat. above 50° N, generally without irrigation) are more typically 15 t/ha/year. The nitrogen requirement of miscanthus appears to be low, with no further response to fertilizer above about 150 kg N/ha/year.

3. TEST LOCATIONS, SIZES, AND DURATIONS

The total area of miscanthus trials in Europe in 1995/96 was about 170 ha (Jorgensen and Venendaal 1997); in 1998 the total was still modest, with Switzerland (300 ha) having the largest area under cultivation (Lewandowski 1998b). The European Miscanthus Productivity Network was established around 1993, with 18 sites participating from 10 countries. Results of these trials have been summarized in a 1997 European Commission (EC) publication, the Miscanthus Handbook (Walsh and McCarthy 1998). However, this publication has not yet been released by the EC for worldwide distribution. The results given here in note form have been drawn from the available literature. Country names are in alphabetical order. *MAP* = mean annual precipitation, *MAT* = mean annual temperature, where reported.

Austria (lat. about 48° N, MAP about 700 mm, MAT 8.8° C), *M. x giganteus*, 3-year old stands @ 10,000/ha, est. 1989, gave 22 t/ha (dry weight). No response to nitrogen fertilizer above 90 kg N/ha, despite added P, K, Mg – possibly due to fertile soil (Schwarz et al. 1994).

Southern Britain (lat. 51-52 N), 4 locations (MAP 500–700 mm), various soil types. *M. x giganteus*, 10–15 t/ha at spring harvest in year 3 (Note low yields because of drought). No response to N fertilizer (Bullard et al. 1996).

Denmark (Hornum, lat. about 56° N). *M. x giganteus* est. 1983, 1986, 1989, 1990, and *M. sinensis* (15 varieties) est. 1990. 70–100 kg N/ha applied. Annual dry matter production 15–25 t/ha, but spring (April) harvesting when drier and more minerals recycled gives 7–10 t/ha. Farmers' trials give 7–9 t/ha (Jorgensen 1996).

Southern Germany, 3 locations (MAP 800–1000 mm, MAT 7.5–10.0° C). *M. x giganteus*. 8–30 t/ha, depending on soil fertility (Lewandowski and Kicherer 1997).

Southern Germany (MAP 606 mm, MAT 9.1° C), 6 genotypes, 3–8 years old, yields as noted in the table below (Hotz et al. 1996).

<u>Genotype</u>		<u>Yield (t/ha)</u>
<i>M. x giganteus</i>	5–10 poor soil	15–24 good soil
<i>M. sinensis</i> "Goliath"	5–6 poor soil	10–19 good soil
<i>M. sinensis</i> "Gracillimus"	2 poor soil	6–17 good soil
<i>M. sinensis</i> "Grosse Fontaine"	5–10 poor soil	15–24 good soil
<i>M. sinensis</i> "Silberfeder"	2–5 poor soil	8–15 good soil
<i>M. type</i> "Ungarn"	4–6 poor soil	9–15 good soil

Western Germany (lat. 51° N, MAP 715 mm, MAT 9.3° C). *M. x giganteus*, 3-year-old stands @ 10,000/ha, est. 1989, gave 30 t/ha dry matter (max.); final spring yield 15–18 t/ha. Low fertilizer requirements — 60 kg N, 8 kg P, 80 kg K, 15 kg magnesium per hectare (Himken et al. 1997)

Germany (4 sites, clay to sand, MAP 565–603 mm, MAT 7.9–9.5° C). *M. x giganteus*. 4- to 6-year-old stands produced 17.0–30.3 t/ha (mean of 3 years). Harvested biomass averaged 10–15 t/ha as a result of preharvest loss of leaves and shoot tips (4–5 t/ha), stubble/residues left in field (1.3–3.1 t/ha), and other loss of stems due to harvesting limitations. Carbon/nitrogen ratio of harvested biomass = 110 (nitrogen content = 0.44%). Nitrogen requirements met by soil mineralization, so nitrogen fertilizer not required (under these temperature/rainfall limited conditions). High transpiration water requirement was confirmed by crop modeling showing soil water depletion. However, miscanthus tended to increase soil organic matter and nitrogen content for sandy soils (further details not available; cited in Boelcke et al. 1998).

Northern Greece (lat. 41° N), *M. x giganteus*, planted on 1.0-m grid, 0.2-ha plot, fertilized and irrigated. Second-year maximum yield (September) = 44 t/ha (Danalatos et al. 1996).

Central Greece (lat. 38° N), *M. x giganteus*, planted at 0.5-m spacing on small plots. 2- to 3-year-old stands yielded 26 t/ha, with little effect of added nitrogen fertilizer or irrigation (Christou et al. 1998).

Southern Italy (lat. 37° N), *M. x giganteus*, small plots, irrigated and fertilized. 30–32 t/ha final (spring) yield in years 2–3 (Foti et al. 1996).

Northwestern Spain (lat. 43° N), *M. x giganteus*, small plots. Mixed results, but no fertilizer effect observed. Demonstrated that 30 t/ha is achievable (Bao Iglesias et al. 1996).

Western Turkey (lat. 38° N, MAP 698 mm, MAT 17.6° C), *M. x giganteus*. 3-year-old stands yielded 28 t/ha, with little effect of added nitrogen fertilizer (Acaroglu and Aksoy 1998).

4. CROP PHYSIOLOGY

Typical maximum leaf area index reported for the European trials (late summer) is around 8 m²/m². Typical maximum canopy height is about 4.0 m, although after over-wintering and leaf drop, the dry stalks are unlikely to be more than 2.5-3.0 m in height. These parameters are not always reported for the various trials.

Possessing the C₄ photosynthetic pathway, miscanthus shows a remarkable combination of high light, water, and nitrogen use efficiencies. Its photosynthetic mechanism appears to be better adapted to low temperatures than that of many other C₄ crops, equipping it for high productivity under relatively cool temperatures. Although water use efficiency is high, the crop may nevertheless require substantial amounts of water for maximal growth, because of its high productivity (Walsh and McCarthy 1998).

5. CULTURAL PRACTICES EMPLOYED

The miscanthus crop is established by planting mechanically divided rhizomes or plantlets micropropagated in tissue culture. Mechanically divided rhizome pieces may be collected with a potato or flower bulb harvester from nursery fields (preferably with sandy soils for ease of tilling), planted at a density of 3–6 plants/m². After 2–3 years, nursery fields are subjected to a single pass of a rotary tiller, breaking up rhizomes into 40- to 100-gram pieces (Fig. 3). This yields a multiplication factor of about 50 ×, in comparison with 100 × for hand cutting of rhizomes from whole plants (Pari 1996; Huisman et al. 1996). Disc harrowing of rhizomes followed by collection of pieces with an automated stone picker has also been used, yielding lower multiplication rates (Wilkins and Redstone 1996). Micropropagation offers potentially much higher multiplication rates (up to 2000 ×; Lewandowski and Kahnt 1993), but these techniques are currently considerably more expensive than mechanical rhizome division.

Larger rhizome pieces, covering with straw or cover crops, and deeper planting all increase overwinter survival and establishment rates, but new cultivars and genotypes (e.g. *M. sinensis* "Goliath" have superior survival rates to *M. x giganteus* (Eppel-Hotz et al. 1998). Similar results were obtained by Schwarz et al. (1998), who also found that micropropagated plantlets were more sensitive to suboptimal conditions (e.g., summer drought). In general, irrigation of newly planted rhizomes appears to improve

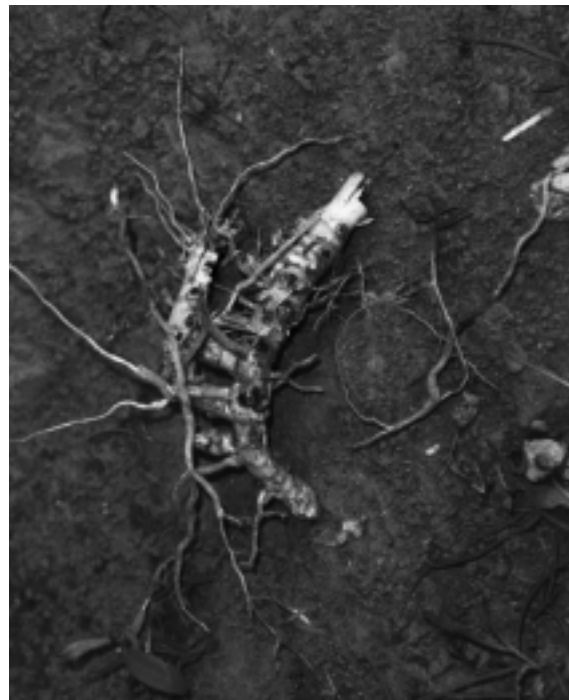


Figure 3. Miscanthus rhizome propagation material ready for planting (length is about 10 cm). Photograph taken June 1996, Vejle, Denmark, by L.L. Wright, ORNL. A color version of the image is on the Bioenergy Information Network website photo gallery (<http://www.esd.ornl.gov/bfdp/>).

establishment rates under drier conditions. Mechanization of rhizome establishment has reduced costs to ECU 350/ha (US\$ 410/ha), and ECU 200/ha (US\$235/ha) may be expected in the future. Earlier cost estimates were ECU 0.04/rhizome (US\$0.047/rhizome), or ECU 400/ha (US\$470/ha) at 10,000/ha (Huisman et al. 1996).

At a typical planting density of 10,000 plants/ha (1-meter spacing), a dense root mat has developed by year 2 or 3, which can prevent leaching of nitrogen. By this time the maximum root density is found at a depth of 0–40 cm, although some roots penetrate down to 250 cm (Koessler and Claupein 1998).

To harvest the miscanthus crop, a chopping forage harvester may be used (*Kemper Champion 3000*), although a row-independent device is needed on older stands where the original planting pattern has become indistinct (Fig. 4). Such harvesting trials have used a chopped length from 11 mm to 44 mm. Baling and bundling are both possible (Fig. 5), but field losses (10% or more due to baling) and stem size/stiffness (bundling) need to be taken into account (Huisman et al. 1996; Venturi and Huisman 1997).



Figure 4 . Harvesting of demonstration plot of *Miscanthus x giganteus* using a *Kemper Champion 4500* forage harvester mounted on a *John Deere* combine. The harvester is modified with hardened cutting blades to withstand the extra wear due to the relatively high silicon content of miscanthus biomass. Photograph taken February 1995, Forchheim, Baden-Württemberg, southern Germany, by Dr. I. Lewandowski, Institute for Crop Production and Grassland Research, University of Hohenheim, Germany. Reproduced by permission. A color version of the image is on the Bioenergy Information Network website photo gallery (<http://www.esd.ornl.gov/bfdp/>).



Figure 5. Baling of miscanthus straw from a demonstration plot, using a Claas baler. Photograph taken February 1995, Forchheim, Baden-Württemberg, southern Germany, by Dr. I. Lewandowski, Institute for Crop Production and Grassland Research, University of Hohenheim, Germany. Reproduced by permission. A color version of the image is on the Bioenergy Information Network website photo gallery (<http://www.esd.ornl.gov/bfdp/>).

6. ENERGY AND CO₂ BALANCE: OTHER ENVIRONMENTAL CONSIDERATIONS

Compared with other bioenergy options, miscanthus appears to fall midway between annual crops (e.g., rapeseed, beet) and woody perennials (e.g., willow, poplar) in terms of its life-cycle analysis. If high yields can be attained, its energy and carbon balance may be favorable (though not as good as woody crops), and nitrous oxide emissions are low compared with other annually harvested crops because of its high nutrient-use efficiency (Kaltschmitt et al. 1996; Lambert et al. 1996). However, energy balance modeling has suggested that overall energy output/input ratio may be as low as 1.1 in the case of co-firing miscanthus with coal because of the high energy requirement for fuel pulverization. In the best case (small-scale heat and power cogeneration with fluidized-bed gasification/gas-turbine technology) the energy balance was 9.6 (Molenaar et al. 1996; Venturi et al. 1998). Miscanthus stands also contain more large animals (mammals, birds) than other herbaceous crops (corn or reeds), possibly because of the greater diversity of canopy structure leading to a higher number and greater range of ecological niches (Jodl et al. 1998). N₂O emissions from normal levels of N-fertilizer application had only a modest effect on net offsets of greenhouse gas warming potential (6% of total CO₂ displacement) (Jorgensen and Jorgensen 1996). Some soil erosion benefits are claimed, but details are not available (Walsh and McCarthy 1998). To date, there are no reports of plant diseases significantly limiting production, but the crop is known to be susceptible to *Fusarium* blight and Barley Yellow Dwarf Luteovirus (Walsh and McCarthy 1998); as with other clonal crop stands, disease may present a significant risk. The European Miscanthus Improvement project has recommended that new genotypes should be sterile (e.g., triploid) as a precaution against them

becoming weeds. There have been some small-scale escapes of fertile ornamental genotypes in Ohio and Indiana which have caused local concern and reinforce the case for releasing only sterile hybrids of miscanthus in the United States (D. Bergdorf, personal communication). It will be necessary to determine whether the likely benefits of miscanthus clearly outweigh any potential harm as an invasive species and to take measures to minimize the risk of harm before U.S. federal funds can be used to develop the species as an energy crop [White House, 1999; Section 2 (3)].

7. ECONOMICS

Economic analysis based upon Danish conditions suggests miscanthus production costs are comparable to those of other annual and perennial energy crops — about 70 ECU/t (US\$82/t) or 4.1 ECU/GJ (US\$4.80/GJ) — making the crop marginally economically viable if agricultural set-aside payments are included. The market price of straw is about 80 ECU/t (US\$94/t) in Denmark; in contrast, the price of wood chips in Sweden is as low as 32 ECU/t (US\$38/t). However, a 10-to 12-year rotation (growing cycle) is required to absorb establishment costs (Parsby 1996; Jorgensen and Venendaal 1997). A crop model for optimizing methods of harvesting, storage, and transport is under development at Wageningen in the Netherlands, but results are not yet available (Huisman et al. 1996; Venturi and Huisman 1998). Economic analysis by the British Agricultural Development and Advisory Service (ADAS) suggests that miscanthus is already viable as a feedstock for specialized paper production in chemical pulp mills, and that energy cropping would be viable under current European conditions (without subsidy) if yields above 18 t/ha/year were obtained on large farms with low fixed costs. Market incentives would be required if yields were only 15 t/ha/year (Walsh and McCarthy 1998).

8. COMBUSTION CHARACTERISTICS

Mineral concentrations are reported to be low at the time of the early spring harvest: 0.09–0.34% N; 0.37–1.12% K; 0.03–0.21% Cl (Lewandowski and Kicherer 1997). Other reports suggest that miscanthus has low mineral and ash content compared with other lignocellulosic species, and that the ratio of useful fertilizer nutrients to heavy metal contaminants in cyclone and grate ashes makes miscanthus, hay, and hemp ash more useful than wood ash (Hasler et al. 1998). The mineral content is low compared with wheat straw, and comparable with willow/poplar coppice. Like other biomass fuels, reactivity/ignition stability is high compared with coal. Overall, the CO₂ balance shows a 90% reduction in emissions compared with coal combustion (Lewandowski et al. 1995).

The composition of miscanthus ash includes approximately 30–40% SiO₂, 20–25% K₂O, 5% P₂O₅, 5% CaO, and 5% MgO — a range of values is reported from different studies (e.g., Moilanen et al. 1996; Hallgren and Oskarsson 1998). Ash behavior (sintering) is no worse than many other biomass ashes, with potassium content a significant factor. Choice of thermal process may be more important (e.g., gasification with gas clean-up) (Moilanen et al. 1996). Sintering of ash under fluidized-bed gasification may cause agglomeration (or, at worst, alkali-induced defluidization). Miscanthus ash showed clear sintering tendencies at temperatures as low as 600° C, compared with reed canary grass and willow (the latter of which was inert up to 900° C). This may be due to the combination of relatively high silica content in miscanthus together with

potassium and fluxing agents such as iron (Hallgren and Oskarsson 1998). However, sintering can be controlled by replacing common fluidized bed materials (silica sand) with calcium-based materials, such as dolomite.

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 a 160-MW powdered fuel combustor (20% co-firing). The plants were already adapted for co-firing with straw: 17 t of miscanthus bales (Heston type, 450 kg, 12% moisture) were burned without major problems in the fluidized bed combustor, and 100 t in the powdered fuel combustor (Visser 1996).

9. CONCLUSIONS AND SUMMARY

The sustained European interest in miscanthus suggests that this novel energy crop deserves serious investigation as a possible candidate biofuel crop for the United States alongside switchgrass (Table 1). Switchgrass may show some advantages over miscanthus (notably lower establishment costs from seed and being a native grass species), but miscanthus is worthy of consideration, at least for certain niche applications. To date, no agronomic trials or trial results for miscanthus are known from the conterminous United States, so its performance under U.S. conditions is virtually unknown. Limited experience has been gained by the USDA/NRCS Plant Materials Center in Michigan, using an ornamental genotype of *Miscanthus sinensis* for vegetative barriers against wind erosion and run-off. Plantings in Ohio, Michigan, and southern Indiana established successfully, but those in Wisconsin did not work; limited experience has also been obtained in Louisiana (D. Bergdorf, personal communication). Small-scale Canadian trials of *Miscanthus x giganteus* began in 1997–1998 outside Montreal (lat. 42.5° N), with initial annual yields at spring harvest of 10–11 t/ha dry weight (R. Samson, personal communication).

Speculating from European data on small plots in agricultural experimental stations, the crop may attain as much as 25 t/ha (10 t/acre dry weight) by fall, but it is usually harvested in early spring, after nutrient recycling and drying has taken place — by which time the yield has reduced to about 15 t/ha (6 t/acre dry weight). Over large areas, under typical agricultural practices, an average of about 8t/ha (3t/acre dry weight) may be expected at harvesttime. The European conditions for these trials range from lat. 50° N to 37° N (roughly from North Dakota to Kentucky, but note that the European climate tends to be warmer and more moderate at the same latitudes than the climate in the United States). Average annual temperatures and rainfall for the European trials range from 7.5° C to 17.5° C (45–63° F), and 500–1000 mm (20–40 in.), with irrigation at the warmer, more southern latitudes. Fertilizer needs appear to be relatively low, depending upon local soil fertility. As with most of the new bioenergy crops, there seems to be a steep "learning curve." Costs are expected to fall and uncertainties to be reduced as first demonstration trials and then commercial plantings become more widespread. Establishment costs appear to be fairly high at present (a wide range is reported from different European countries), although these may be expected to fall as improved management techniques are developed.

Table 1. Comparison of the properties of miscanthus and switchgrass

Fuel property	Miscanthus ^a (<i>Miscanthus x giganteus</i>)	Switchgrass ^b (<i>Panicum virgatum</i>)
Gross heating value (dry; GJ/t)	17.1–19.4	18.3
Net energy content (dry; GJ/t)	15.8–16.5	N/A
Moisture content at harvest (%)	15	15
Chopped density at harvest (kg/m ³)	70–100	108
Baled density [compacted bales] (kg/m ³)	130–150 [300]	105–133
Holocellulose (cellulose + hemicellulose) (%)	64–71	54–67
Ash content (%)	1.5–4.5	4.5–5.8
Ash fusion (melting) temperature (C) [temperature at which some sintering observed]	1090 [600]	1016
Sulfur content (%)	0.1	0.12

^aData for miscanthus from Acaroglu and Aksoy (1998); Nikolaisen (1998); Hallgren and Oskarsson (1998); Huisman et al. (1996); Moilanen et al. (1996); Papatheofanous et al. (1996).

^bData for switchgrass from McLaughlin et al. (1996).

10. CONTACTS FOR FURTHER INFORMATION

Dr. Iris Lewandowski
Institute for Crop Production and Grassland Research
University of Hohenheim (340)
D 70599 Stuttgart
GERMANY
E-mail: lewandow@uni-hohenheim.de

Dr. S. McCarthy/Dr. M. Walsh
Hyperion Energy Systems Ltd.
Main Street
Watergrasshill, Co. Cork
IRELAND
Tel. +353 21 889461
Fax: +353 21 889465
E-mail: energy@indigo.ie

European Energy Crops InterNetwork Web site: <http://btg.ct.utwente.nl/eeci/>

For limited North American experience with (a) establishing miscanthus for soil erosion control, and (b) evaluation of productive potential:

(a) Dr. David Bergdorf
Plant Materials Specialist
USDA Natural Resource Conservation Service
1405 South Harrison Road
East Lansing, MI 48823
USA
Tel. +1 (517) 337-6701 x1211
Fax: +1 (517) 337-6905
Email: dave@mi.nrcs.usda.gov

(b) Roger Samson
Executive Director
Resource Efficient Agricultural Production (REAP) - Canada
Box 125, Maison Glenaladale
Ste. Anne de Bellevue
Quebec H9X 3V9
CANADA
Tel. +1 (514) 398-7743
Fax: +1 (514) 398-7972
E-mail: reap@interlink.net
<http://infosys.agrenv.mcgill.ca/~reap/>

11. REFERENCES

(For references whose titles are not explicit, the content is indicated in brackets, e.g., [YIELD RESULTS]).

- Acaroglu, M., and A. S. Aksoy. 1998. Third year growing results of C₄ energy plant *Miscanthus sinensis* in producing energy from biomass. pp. 758-759. In *Biomass for Energy and Industry*, Proceedings of the 10th European Biomass Conference, Würzburg, Germany, June 1998. C.A.R.M.E.N. Publishers, Rimpf, Germany.
- Bao Iglesias, M., J. L. Rodriguez R., I. Crespo R., and J. Lamas A. 1996. *Miscanthus sinensis* plantations in Galicia, north-west Spain: results and experience over the last three years. pp. 608-612. In *Biomass for Energy and the Environment*, Proceedings of the 9th European Bioenergy Conference, Copenhagen, Denmark, June 1996. Pergamon/Elsevier Publishers.
- Boelcke, B., S. Buech, and S. Zacharias. 1998. Effects of miscanthus cultivation on soil fertility and the soil water reservoir. pp. 911-914. In *Biomass for Energy and Industry*, Proceedings of the 10th European Biomass Conference, Würzburg, Germany, June 1998. C.A.R.M.E.N. Publishers, Rimpf, Germany. [GERMAN YIELD RESULTS]
- Bullard, M. J., D. G. Christian, and C. Wilkins. 1996. The potential of graminaceous biomass crops for energy production in the UK: An overview. pp. 592-597. In *Biomass for Energy and the Environment*, Proceedings of the 9th European Bioenergy Conference, Copenhagen, Denmark, June 1996. Pergamon/Elsevier Publishers. [YIELD RESULTS]
- Christou, M., D. Papavassiliou, E. Alexopoulou, and A. Chatziathanassiou. 1998. Comparative studies of two potential energy crops in Greece. pp. 935-938. In *Biomass for Energy and Industry*, Proceedings of the 10th European Biomass Conference, Würzburg, Germany, June 1998. C.A.R.M.E.N. Publishers, Rimpf, Germany. [YIELD RESULTS]
- Danalatos, N. G., C. Dalianis, and S. Kyritsis. 1996. Growth and biomass productivity of *Miscanthus sinensis* "giganteus" under optimum cultural management in north-eastern Greece. pp. 548-553. In *Biomass for Energy and the Environment*, Proceedings of the 9th European Bioenergy Conference, Copenhagen, Denmark, June 1996. Pergamon/Elsevier Publishers.
- Eppel-Hotz, A., S. Jodl, W. Kuhn, K. Marzini, and W. Munzer. 1998. Miscanthus: New cultivars and results of research experiments for improving the establishment rate. pp. 780-786. In *Biomass for Energy and Industry*, Proceedings of the 10th European Biomass Conference, Würzburg, Germany, June 1998. C.A.R.M.E.N. Publishers, Rimpf, Germany.
- Foti, S., S. L. Cosentino, C. Patane, and P. Guarnaccia. 1996. Growth and yield of C₄ species for biomass production in the Mediterranean environment. pp. 616-621. In *Biomass for Energy and the Environment*, Proceedings of the 9th European Bioenergy Conference, Copenhagen, Denmark, June 1996. Pergamon/Elsevier Publishers. [ITALY YIELD RESULTS]
- Hallgren, A. L., and J. Oskarsson. 1998. Minimization of sintering tendencies in fluidized-bed gasification of energy crop fuels. pp. 1700-1703. In *Biomass for Energy and Industry*, Proceedings of the 10th European Biomass Conference, Würzburg, Germany, June 1998. C.A.R.M.E.N. Publishers, Rimpf, Germany.
- Hasler, P., T. Candinas, and T. Nussbaumer. 1998. Utilization of ashes from the combustion of hay, miscanthus, hemp, straw and wood as fertilizer. pp. 192-195. In *Biomass for Energy and Industry*, Proceedings of the 10th European Biomass Conference, Würzburg, Germany, June 1998. C.A.R.M.E.N. Publishers, Rimpf, Germany.

- Himken, M., J. Lammel, D. Neukirchen, U. Czipionka-Krause, and H.-W. Olf. 1997. Cultivation of *Miscanthus* under West European conditions: Seasonal changes in dry matter production, nutrient uptake and remobilization. *Plant and Soil* 189:117-126.
- Hotz, A., W. Kuhn, and S. Jodl. 1996. Screening of different miscanthus cultivars in respect of yield production and usability as a raw material for energy and industry. pp. 523-527. In *Biomass for Energy and the Environment*, Proceedings of the 9th European Bioenergy Conference, Copenhagen, Denmark, June 1996. Pergamon/Elsevier Publishers.
- Huisman, W., G.J. Kasper, and P. Venturi. 1996. Technical and economic feasibility of the complete production — transport chain of *Miscanthus x giganteus* as an energy crop. Paper presented at the First European Energy Crops Conference, Enschede, The Netherlands, September 30-October 1, 1996.
- Jodl, S., A. Eppel-Hotz, and K. Marzini. 1998. Examination of the ecological value of miscanthus expanses — faunistic studies. pp. 778-779. In *Biomass for Energy and Industry*, Proceedings of the 10th European Biomass Conference, Würzburg, Germany, June 1998. C.A.R.M.E.N. Publishers, Rimpfing, Germany. [BIODIVERSITY]
- Jorgensen, U. 1996a. Miscanthus yields in Denmark. pp. 48-53. In *Biomass for Energy and the Environment*, Proceedings of the 9th European Bioenergy Conference, Copenhagen, Denmark, June 1996. Pergamon/Elsevier Publishers.
- Jorgensen, U. (1996b). Genotypic variation in dry matter accumulation and content of N, K and Cl in miscanthus in Denmark. *Biomass and Bioenergy* 12:155-169. [YIELD RESULTS]
- Jorgensen, R.N., and B.J. Jorgensen. 1996. The effect of N₂O emission on the net CO₂ displacement by energy crop production. pp.1701-1706. In *Biomass for Energy and the Environment*, Proceedings of the 9th European Bioenergy Conference, Copenhagen, Denmark, June 1996. Pergamon/Elsevier Publishers.
- Jorgensen, U., and R. Venendaal. 1997. European energy crops overview: species, costs and commercial development. R.P. Overend and E. Chornet (eds.). pp.57-69. In *Making a Business from Biomass*. Proceedings of the 3rd Biomass Conference of the Americas, Montreal. Pergamon/Elsevier Publishers.
- Kaltschmitt, M., G.A. Reinhardt, and T. Stelzer. 1996. LCA of biofuels under different environmental aspects. pp. 369-386. In *Biomass for Energy and the Environment*, Proceedings of the 9th European Bioenergy Conference, Copenhagen, Denmark, June 1996. Pergamon/Elsevier Publishers. [LIFE CYCLE ANALYSIS]
- Koessler, C., and W. Claupein. 1998. Root systems of miscanthus in different growing periods. pp. 369-386. In *Biomass for Energy and Industry*, Proceedings of the 10th European Bioenergy Conference, Würzburg, Germany, June 1998. C.A.R.M.E.N. Publishers, Rimpfing, Germany. pp. 842-845. [ROOTING DEPTH]
- Lambert, L., G. Gaillard, and J.-L. Hersener. 1996. Energy balance of the thermic use of *Miscanthus* in comparison with wood and fuel oil. pp. 634-637. In *Biomass for Energy and the Environment*, Proceedings of the 9th European Bioenergy Conference, Copenhagen, Denmark, June 1996. Pergamon/Elsevier Publishers.
- Lewandowski, I., and G. Kahnt. 1993. Development of a tissue culture system with unemerged inflorescences of *Miscanthus 'giganteus'* for the induction and regeneration of somatic embryoids. *Beitrage zur Biologie der Pflanzen* 67:439-451.
- Lewandowski, I., A. Kicherer, and P. Vonier. 1995. CO₂-balance for the cultivation and combustion of *Miscanthus*. *Biomass and Bioenergy* 8:81-90.
- Lewandowski, I. and A. Kicherer. 1997. Combustion quality of biomass: Practical relevance and experiments to modify the biomass quality of *Miscanthus x giganteus*. *European J. Agronomy* 6:163-177.

- Lewandowski, I. 1998a. EMI: European Miscanthus Improvement – the results of the first year of a miscanthus breeding project. pp. 930–932. In *Biomass for Energy and Industry*, Proceedings of the 10th European Biomass Conference, Würzburg, Germany, June 1998. C.A.R.M.E.N. Publishers, Rimpf, Germany.
- Lewandowski, I. 1998b. Production of miscanthus and switchgrass. pp. 13–21. In *Production and Use of Perennial Rhizomatous grasses (PRG) in the Energy and Industrial Sector of Europe*. Proceedings of the 1st Workshop held within 10th Bioenergy Conference, Würzburg, Germany, June 1998. [OVERVIEW]
- McLaughlin, S.B., R. Samson, D. Bransby, and A. Wiseloge. 1996. Evaluating physical, chemical and energetic properties of perennial grasses as biofuels. pp. 1–8. In *Bioenergy '96*, Proceedings of the 7th National Bioenergy Conference, Nashville, Sept. 1996.
- Moilanen, A., M. Nieminen, K. Sipilä, and E. Kurkela. 1996. Ash behavior in thermal fluidized-bed conversion processes of woody and herbaceous biomass. pp. 1227–1232. In *Biomass for Energy and the Environment*, Proceedings of the 9th European Bioenergy Conference, Copenhagen, Denmark, June 1996. Pergamon/Elsevier Publishers.
- Molenaar, J.A., W. Huisman, and P. Venturi. 1996. Energy consumption and costs of the production chain of *Miscanthus x giganteus*. pp. 867–872. In *Biomass for Energy and the Environment*, Proceedings of the 9th European Bioenergy Conference, Copenhagen, Denmark, June 1996. Pergamon/Elsevier Publishers.
- Nikolaissen, L.S. 1998. PRG grasses for energy use. pp. 50–54. In *Production and Use of Perennial Rhizomatous grasses (PRG) in the Energy and industrial Sector of Europe*. Proceedings of the 1st Workshop held within 10th European Bioenergy Conference, Würzburg, June 1998. [FUEL CHARACTERISTICS]
- Papatheofanous, M.G., E.G. Koukios, G. Marton, and J. Dencs. 1996. Characterization of *Miscanthus sinensis* potential as an industrial and energy feedstock. pp. 504–508. In *Biomass for Energy and the Environment*, Proceedings of the 9th European Bioenergy Conference, Copenhagen, Denmark, June 1996. Pergamon/Elsevier Publishers. [CELLULOSE CONTENT]
- Pari, L. 1996. First trials on *Arundo donax* and miscanthus rhizomes harvesting. pp. 889–894. In *Biomass for Energy and the Environment*, Proceedings of the 9th European Bioenergy Conference, Copenhagen, Denmark, June 1996. Pergamon/Elsevier Publishers.
- Parsby, M.S. 1996. Economic assessment of straw and energy crops for agriculture and carbon dioxide reduction. pp. 1689–1694. In *Biomass for Energy and the Environment*, Proceedings of the 9th European Bioenergy Conference, Copenhagen, Denmark, June 1996. Pergamon/Elsevier Publishers.
- Schwarz, H., P. Liebhard, K. Ehrendorfer, and P. Ruckebauer. 1994. The effect of fertilization on yield and quality of *Miscanthus sinensis* ‘giganteus.’ *Industrial Crops and Products* 2:153–159. [AUSTRIA YIELD RESULTS]
- Schwarz, K.-U., J.B. Kjeldsen, W. Munzer, and R. Junge. 1998. Low cost establishment and winter survival of *Miscanthus x giganteus*. pp. 947–950. In *Biomass for Energy and Industry*, Proceedings of the 10th European Biomass Conference, Würzburg, Germany, June 1998. C.A.R.M.E.N. Publishers, Rimpf, Germany.
- Visser, I. 1996. Co-combustion of miscanthus and coal. pp. 1460–1461. In *Biomass for Energy and the Environment*, Proceedings of the 9th European Bioenergy Conference, Copenhagen, Denmark, June 1996. Pergamon/Elsevier Publishers.
- Venturi, P., and W. Huisman. 1997. State of art of the production of *Miscanthus x giganteus* in Europe. pp. 155–165. In *Making a Business from Biomass*. Proceedings of the 3rd Biomass Conference of the Americas, Montreal (eds. R.P. Overend and E. Chornet). Pergamon/Elsevier Publishers.

- Venturi, P. and W. Huisman. 1998. Modeling the optimization of primary production costs of miscanthus. pp. 806–809. In *Biomass for Energy and Industry*, Proceedings of the 10th European Biomass Conference, Würzburg, Germany, June 1998. C.A.R.M.E.N. Publishers, Rimpf, Germany.
- Venturi, P., W. Huisman, and J. Molenaar. 1998. Mechanization and costs of primary production chains for *Miscanthus x giganteus* in the Netherlands. *Journal of Agricultural Engineering Research* **69**:209–215.
- Walsh, M. and S. McCarthy. 1998. Miscanthus handbook. pp. 1071–1074. In *Biomass for Energy and Industry*, Proceedings of the 10th European Bioenergy Conference, Würzburg, Germany, June 1998. C.A.R.M.E.N. Publishers, Rimpf, Germany.
- White House (1999) *Executive Order on Invasive Species 1999-02-03*. The White House, Washington, DC, 3-Feb-1999.
- Wilkins, C., and S. Redstone. 1996. Biomass production for energy and industry in the far South-West of England. pp. 799–806. In *Biomass for Energy and the Environment*, Proceedings of the 9th European Bioenergy Conference, Copenhagen, Denmark, June 1996. Pergamon/Elsevier Publishers. [RHIZOME HARVESTING]

INTERNAL DISTRIBUTION

- | | | | |
|-------|------------------|--------|-----------------------------|
| 1-50. | J. H. Cushman | 59. | D. E. Reichle |
| 51. | D. E. Fowler | 60. | J.M.O. Scurlock |
| 52. | S. G. Hildebrand | 61. | V. R. Tolbert |
| 53. | G. K. Jacobs | 62. | G. A. Tuskan |
| 54. | P. Kanciruk | 63. | M. E. Walsh |
| 55. | J. M. Loar | 64. | S. D. Wullschleger |
| 56. | S. B. McLaughlin | 65. | Central Research Library |
| 57. | T. E. Myrick | 66-68. | ESD Library |
| 58. | R. J. Olson | 69-70. | Laboratory Records Dept. |
| | | 71. | Laboratory Records, ORNL-RC |

EXTERNAL DISTRIBUTION

72. Clive Beale, Writtle College, Chelmsford, Essex CM1 3RR, United Kingdom
73. David Bergdorf, Plant Materials Specialist, USDA Natural Resource Conservation Service, 1405 South Harrison Road, East Lansing, MI 48823
74. David Bransby, Auburn University, Dept. of Agronomy & Soils, 202 Funchess Hall, Auburn, AL 36839-5110
75. M. Broido, Director, Environmental Sciences Division, ER-74, Department of Energy, 19901 Germantown Road, Germantown, MD 20874
76. Dudley Christian, Rothamstead Experimental Station, Harpenden Herts. AL5 2JQ, United Kingdom
77. John Clifton Brown, Institute for Crop Production and Grassland Research, University of Hohenheim (340), D 70599 Stuttgart, GERMANY
78. Joe Bouton, University of Georgia, Department of Crop and Soil Sciences, Room 3111, Athens, GA 30602-7272
79. Bob Conger, University of Tennessee, Dept. of Plant and Soil Science, Knoxville, TN 37901-1071
80. Ray Costello, U.S. Dept. of Energy, Biomass Power Program, 1000 Independence Ave, SW EE-13, Washington, DC 20585
81. E. G. Cumeasty, Assistant Manager for Laboratories and Site Manager, Department of Energy, Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, TN 37831-6269
82. John Ferrell, U.S. Dept. of Energy, Office of Fuels Development, 1000 Independence Avenue, EE-31/MS:6B-025 FORS, Washington, DC 20585
83. J. P. Giesy, College of Natural Science, Department of Zoology, Michigan State University, 203 Natural Science Building, East Lansing, MI 48824-1115
84. David Glassner, National Renewable Energy Laboratory, 1617 Cole Boulevard, Golden, CO 80401
85. David Hall, Division of Life Sciences, King's College London, Campden Hill Road, London W8 7AH, United Kingdom
86. Willem Huisman, Farm Technology Group, Wageningen Agricultural University, Bomenweg 4, 6703 HD Wageningen, THE NETHERLANDS
87. Mark Hussey, Texas A&M University, Dept. of Soil and Crop Sciences, College Station, TX 77843

88. Jacob Kaminsky, U.S. Dept. of Energy, Biomass Power Program, 1000 Independence Avenue, EE-13, Washington DC 20585
89. Iris Lewandowski, Institute for Crop Production and Grassland Research, University of Hohenheim (340), D 70599 Stuttgart, GERMANY
90. S.P. Long, Dept. of Biology, University of Essex, Colchester CO4 3SQ, United Kingdom
91. A. A. Lucier, National Council of the Paper Industry For Air and Stream Improvement, Inc., P.O. Box 13318, Research Triangle Park, NC 27709-3318
92. Michael C. MacCracken, Director, Office of the U.S. Global Change Research Program, Code YS-1, 300 E Street, SW, Washington, DC 20546
93. Mike Materne, Plant Materials Specialist, P.O. Box 16030, University Station, Baton Rouge, LA 70893
94. S. McCarthy, Hyperion Energy Systems Ltd., Main Street, Watergrasshill Co., Cork, IRELAND
95. William Ocumpaugh, Texas Agricultural Experiment Station, HCR 2, Box 43-C, Beeville, TX 78102-9410
96. David Parrish, Virginia Tech, Crop, Soils, and Env. Sciences, Blacksburg, VA 24061-0404
- 97-98. Office of Scientific and Technical Information, P.O. Box 62, Oak Ridge, TN 37831
99. L. Robinson, Director, Environmental Sciences Institute, Florida A&M University, Science Research Facility, 1520 S. Bronough Street, Tallahassee, FL 32307
100. Roger Samson, Resource Efficient Agricultural Production (REAP)-Canada, Box 125, Maison Glenaladale, Ste. Anne de Bellevue, Quebec H9X 3V9, CANADA
101. John Sheehan, National Renewable Energy Laboratory, 1617 Cole Blvd., Golden, CO 80401
102. Sarah Sprague, U.S. Dept. of Energy, Office of Fuels Development, 1000 Independence Avenue, EE-31/MS:6B-025 FORS, Washington, DC 20585
103. J. M. Tiedje, University Distinguished Professor and Director, Center for Microbial Ecology, Michigan State University, 540 Plant and Soil Sciences Building, East Lansing, MI 48824
104. Anthony Turhollow, 1511 E. 2050 North, North Logan, UT 84341-8804
105. Ken Vogel, University of Nebraska, USDA-ARS, 344 Keim Hall, P.O. Box 830937, Lincoln, NE 68583-0937