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Miscanthus: European experience with a novel energy crop

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Abstract

Miscanthus is a tall perennial rhizomatous grass with C_4 photosynthesis which originated in East Asia. This article provides an overview of the most important results and experience gained with miscanthus in Europe over the past 10 years. Field trials have been established throughout Europe from the Mediterranean to southern Scandinavia. Most reported trials have used a vigorous sterile clone *Miscanthus x giganteus*, which has been propagated vegetatively either by rhizome cutting or *in vitro* culture. Yields in autumn have been reported in excess of 30 t ha^{-1} (12 t $acre^{-1}$) for irrigated trials in southern Europe. Without irrigation autumn yields of 10–25 t ha^{-1} (dry matter) can be expected. The quality of miscanthus biomass for combustion is in some respect comparable to woody biomass and normally improves by delaying harvesting until the spring, although harvestable yields are thus reduced by 30–50% compared with autumn yields. Different technical options for establishment, harvesting and handling of miscanthus have been developed and these significantly effect production costs. Miscanthus production is characterized by low fertilizer and pesticide requirements making it a relatively benign crop environmentally. The main limitations to miscanthus production from *M. x giganteus* are the high establishment costs, poor over-wintering at some sites and insufficient water supply in southern regions of Europe. New agronomic techniques and new genotypes with improved characteristics are being developed and screened over the wide range of ecological conditions in Europe. Against this background of European experience the prospects for growing miscanthus in North America are discussed.

Keywords: Miscanthus; Biofuel; Energy crop; Productivity; Quality; Management; Harvest; Drying; Storage; Combustion; Economics

1. Introduction

Miscanthus is a perennial rhizomatous grass with the C_4 photosynthetic pathway. The genus *Miscanthus* has its origins in the tropics and subtropics, but different species are found throughout a wide climatic range in East Asia [1]. The remarkable adaptability of miscanthus to different environments [2] makes this novel crop suitable for establishment and distribution under a range of European and North American climatic conditions.

Miscanthus was first cultivated in Europe in the 1930s, when it was introduced from Japan. A number of ornamental varieties of miscanthus are known to

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Fig. 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.

exist under various common names. A sterile hybrid horticultural genotype, *Miscanthus x giganteus* [1] GREEF et DEU [1] was brought back to Denmark by Aksel Olsen in 1935, and was observed to have exceptionally vigorous growth [5]. Extensive field trials of *M. x giganteus* GREEF et DEU have been carried out in northern Europe since 1983, and have shown the capacity for high yields, over 20 t dry matter ha^{-1} $year^{-1}$ [6,7] (Fig. 1). Based upon promising preliminary results, an international research project funded under the European JOULE program was initiated in 1989. Field trials were established in Denmark, Germany, Ireland and the UK to investigate the biomass potential of *M. x giganteus* across northern Europe. In 1993, a larger project was set up under the European AIR program, which extended the distribution of field trials into southern Europe, including Greece, Italy and Spain [8]. Nationally funded projects in Denmark, Netherlands, Germany, Austria and Switzerland supported research on propagation and establishment, management practices, harvest and handling of miscanthus.

These trials have shown both the potential of *M. x giganteus* in Europe, and its limitations. Key agronomic advantages are its high yields, and its low fertilizer and pesticide inputs. Tests have shown that *M. x giganteus* biomass can be used as solid fuel, in construction materials such as pressed particle-board, and as a source of cellulose. Key disadvantages include relatively high establishment costs, narrow genetic base, and low hardiness in the first winter following establishment of *M. x giganteus*.

The aim of this article is to review European research results and to describe the current options for miscanthus production. From the experience gained with miscanthus in Europe, conclusions can be drawn for transfer and application in other parts of the world, such as North America.

2. Crop biology

The genus *Miscanthus* occurs within the orthoseral (tall) grasslands of East Asia, from the tropics and subtropics to the Pacific Islands, the warm temperate regions and the subarctic [1,2,9,10]. Taxonomically this genus belongs to the subtribe Saccharineae of the tribe Andropogoneae, which is in the family Graminae (Poaceae). However, the taxonomy is confused within the *Miscanthus* genus [11].

Since miscanthus has a basic chromosome number of 19, the triploid genotype *Miscanthus x giganteus* GREEF et DEU possesses 57 somatic chromosomes, and is probably a natural hybrid involving *Miscanthus sacchariflorus* (diploid) and *Miscanthus sinensis* (tetraploid) [1]. As a consequence of its triploidy, *M. x giganteus* is sterile and cannot form fertile seeds [5].

Miscanthus is among very few grass genera naturally occurring in temperate climates which possess the C_4 photosynthetic pathway. Plants with C_4 photosynthesis have the potential to out-yield plants with C_3 photosynthesis because of higher radiation, water and nitrogen-use efficiencies, but they require warmer conditions than C_3 plants to initiate growth in spring time [12]. Controlled-environment experiments have shown that *M. x giganteus* begins growth from the dormant winter rhizome when soil temperatures reach 10 to 12°C [13]. The threshold temperature for leaf expansion of plants which have begun to grow ranges between 5 and 10°C, and considerable variation exists in the thermal response of leaf expansion for different genotypes [14].

[1] The genotype *M. x giganteus* GREEF et DEU [1] used in the field trials described here has several synonyms. These include *M. sinensis* var. 'Giganteus' [3], *M. x ogiformis* Honda 'Giganteus' [4] and Miscanthus 'Giganteus' [5].

Radiation use efficiencies above those obtained for C_3 crops (more than $3.29\,g\,MJ^{-1}$ [dry matter]) have been found in the UK [15] and in France [16] for *M. x giganteus*. Despite this, lower conversion efficiencies equivalent to those of native C_3 crops have also been determined in the Netherlands [17] and Ireland [18] (2.4 and $2.6\,g\,MJ^{-1}$, respectively) indicating that C_4 photosynthesis is not always more efficient.

Water-use efficiency has been estimated from pot experiments to range from 250 to $340\,g\,g^{-1}$ (mass of water per unit dry matter, also equivalent to litres of water per kilogram dry matter) [19] and 80 to $300\,g\,g^{-1}$ from field trials [20,21] for *M. x giganteus*. Although its water-use efficiency is higher than most C_3 crops, growth is often water-limited [22,23].

The rhizome plays a key role in nutrient economics in miscanthus as well as being the over-wintering organ. This high nitrogen-use efficiency of miscanthus is mainly attributable to the translocation of the nitrogen to the shoot in spring and then re-translocation to the rhizomes at the end of the growing season when the plant senescences [24]. In the first winter following planting, the rather shallow and under-developed rhizomes have often been destroyed by cold and or wet conditions [25]. There are no reports of over-wintering problems in the second and subsequent winters in *M. x giganteus*. For full establishment of *M. x giganteus* at least two growing seasons are required before really vigorous shoot growth occurs.

3. Field experiments in Europe

3.1. Varieties cultivated

Although the majority of European trials have involved clones of *M. x giganteus*, other genotypes are now being evaluated (see Table 1). The contribution of *M. sacchariflorus* to the genome of *M. x giganteus* is thought to provide adaptation to warmer climates, whereas *M. sinensis* provides genetic resources for cooler regions [26]. Indeed, an important advantage of *M. sinensis* genotypes over *M. x giganteus* is their improved winter hardiness [27,28]. Financed by the European Commission (EC), the European Miscanthus improvement (EMI) project continues to develop breeding methods for the production of new miscanthus hybrids using genetic material from the gene pools of *M. sinensis* and *M. sacchariflorus*. In 1997, extensive trials began of 15 genotypes across five different locations in Europe, from Sweden to Portugal. Initial results showed that hardier genotypes than *M. x giganteus* can be selected, which can achieve similar yields by the second year of establishment [25]. In addition, different genotypes have been selected and compared in field trials in Denmark, where *M. sinensis* genotypes out-yielded *M. x giganteus* [26].

Differences in yield and quality between the genotypes can be explained by their distinctive physiological rhythms and morphologies. Late flowering and senescing genotypes have a more extended growing season, leading to higher yields, but they also show higher concentrations of minerals at harvest, especially N, as relocation to the rhizomes starts later. *M. sinensis* genotypes are characterized by thinner stems, which can increase the leaching of Cl and K but at the same time increase leafiness [26].

3.2. Test locations and scale

The total area of miscanthus trials in Europe in 1995/96 was about 170 ha [29]; in 1998 the total was still modest, with Switzerland (300 ha) having the largest area under cultivation. The European Miscanthus Productivity Network was established in 1993, with 18 sites participating from 10 countries [8]. Some results of these trials are available in the literature and have been summarized in Table 1. The largest national miscanthus project ran from 1991 to 1994 in Germany and was led by the energy company Veba Oel AG. A total of 70 ha was established at 20 locations in Germany, although most of this has now been removed.

4. Cultural practices

4.1. Crop establishment

4.1.1. Propagation

As a sterile hybrid, *M. x giganteus* does not form seeds and has to be propagated vegetatively. Mechanically divided rhizomes, plants grown from rhizome pieces divided manually, or plantlets

Table 1
Miscanthus yields reported for Europe, by latitude (North to South)

Location and latitude	Mean annual temperature/ precipitation	Genotype	Age of stand	Stand density (plants m^{-2})	Harvest period	Yield (t ha^{-1} $year^{-1}$, dry matter) and remarks	Notes on fertilization, irrigation	Reference
Denmark 56°N	7.3°C 693 mm	*M. x giganteus*	4–6 5		April	7–15 7–9 (farmers trials)	70–100 kg N had no yield effect	[94]
Denmark 56°N	7.3°C 693 mm	*M. x giganteus* *M. sinensis*	3–5 3–5	4 4	January January	5–10 6–11	0–150 kg N had no yield effect	[26]
Northern Germany 53–54°N	8.0–8.8°C 700–720 mm	*M. x giganteus*	3–4	1–3	December	15–24	All trials received 80 kg N ha^{-1} a^{-1}	[39]
Central Germany 50–52°N	6.3–9.0°C 680–760 mm	*M. x giganteus*	3–4	2	December	4–20		
Southern Germany 49°N	7.4–8.5°C 520–810 mm	*M. x giganteus*	3–4	1–3	December	9–19		
Northern Germany 53°N	7.9–8.8°C 547–600 mm	*M. x giganteus*	4–5	1–3	February/ March	8–14	0–100 kg N had no yield effect	[76]
Central Germany 50°N	9.1°C 606 mm	*M. x giganteus*	6	1–2		6–20		
Southern Britain 51–52°N	500–700 mm	*M. x giganteus*	3	1	Spring	10–15	No response to fertilizer N, drought occurred	[95]
Central Germany 52°N	8.7°C 617 mm	*M. x giganteus*	3–4	1–4	February/ March	15–22	Irrigated when necessary, 0–240 kg N, 60 kg N optimal	[19]

Central Germany 51°N	9.3°C 715 mm	*M. x giganteus*	3	1	Spring	15–18	Low fertilizer requirements – 60 kg N, 8 kg P, 80 kg K, 15 kg Mg ha^{-1}	[43]
Central Germany 50°N	9.1°C 606 mm	*M. x giganteus* *M. sinensis* "Goliath" *M. sin.* "Gracillimus" *M. sin.* "Grosse Fontaine" *M. sin.* "Silberfeder" *M.* type "Ungarn"	3–8	1		5–10 poor soil, 15–24 good soil 5–6 poor soil, 10–19 good soil 2 poor soil, 6–17 good soil 3–4 poor soil, 10–15 good soil 2–5 poor soil, 8–15 good soil 4–6 poor soil, 9–15 good soil		[55]
Southern Germany 48–49°N	7.5–9.8°C 691–850 mm	*M. x giganteus*	2–4	2	February	8–30	0–150 kg, 100 kg N highest yield, no irrigation	[49]
Northern Switzerland 47°N	7.5°C 944–1066 mm	*M. x giganteus*	1–2	3–5	January	13–19	0–80 kg N	[23]
Austria 48°N	8.8°C 700 mm	*M. x giganteus*	3	1		22	No response to N fertilizer above 90 kg N ha^{-1}	[3]
North-west Spain 43°N	12.1–14.7°C 1866–1945 mm	*M. x giganteus*	4	4		14–34	0–120 kg N had no yield effect	[96]
Northern Greece 41°N		*M. x giganteus*	2	1	September	44	fertilized and frequently irrigated	[56]
Central Greece 38°N		*M. x giganteus*	2–3	5	End of growing season	26	little effect of added N, 40–80 kg N, irrigated	[42]
Western Turkey 38°N	17.6°C 698 mm	*M. x giganteus*	3	1		28	0–200 kg N little effect of added N fertilizer N	[97]
Southern Italy 37°N	450 mm	*M. x giganteus*	2–3	4	Final spring	30–32	120 kg N, irrigated	[98]

micro-propagated in tissue culture are used. Methods for mechanical division of rhizomes in the field, so-called macro-propagation, were first developed in Denmark [30]. According to this method, nursery fields are subjected to 1–2 passes of a rotary tiller after 2–3 years, breaking up rhizomes into 20–100 g pieces. Rhizome pieces are collected with a stone picker, potato or flower bulb harvester from nursery fields. The rhizomes and root pieces of the rhizomes must not dry out and, therefore, the storage should be as short as possible and the rhizomes planted just after harvest [31]. This may be done with conventional planting machinery, but a recently developed machine (*Hvidsted Energy Forest, Denmark*) can handle about 5 t of bulk harvested rhizomes, which are planted in rows [31]. With a capacity of 0.3–0.5 ha h^{-1}, this single-operator machine is expected to further reduce costs due to its low labor demand.

Macro-propagation yields a multiplication factor of up to 50×, compared to about 100× for hand cutting of rhizomes from whole plants [32,33]. Disc harrowing rhizomes followed by collection of pieces with an automated stone picker has also been used, yielding lower multiplication rates [34].

Mechanization of rhizome establishment has reduced cost of propogation material to 350 Euro ha^{-1} (US$ 128 $acre^{-1}$), and 200 Euro ha^{-1}(US$74 $acre^{-1}$) may be expected in the future. Earlier cost estimates per plant were 0.04 Euro (US$0.036), or 400 Euro ha^{-1} (US$147 $acre^{-1}$) at a density of 10,000 plants ha^{-1} (4000 per acre) [33].

However, most stands in Europe have been, and still are, established by using micro-propagated plants, produced by in vitro tillering. For an overview of different micro-propagation methods see Lewandowski [35]. The costs for micro-propagated plants are about 0.3 Euro (US$0.27) per plant, equivalent to costs of planting material per hectare of 3000–6000 Euro (US$2730–5460), for typical densities of one or two plants per square metre (10,000–20,000 ha^{-1}).

Hybridisation by inter- and intraspecific crosses of *M. sinensis* and *M. sacchariflorus* genotypes carried out by the breeder in the European Miscanthus Improvement project resulted in fertile seeds. However, it is not yet clear whether field establishment by seeds is possible since miscanthus seeds are very small (1000 seeds weigh about 250–1000 mg), have low nutrient reserves, and require high temperature and moisture for germination [36].

4.1.2. Site preparation and planting

To prepare the soil for planting, ploughing to 20–30 cm depth is recommended. Harrowing shortly before planting reduces competition from weeds. The young miscanthus plants from micro- or rhizome propagation are frost-sensitive and, therefore, should be planted in spring when no more frost ($< -3^\circ C$) occurs. Planting densities in various trials have ranged from 1 to 4 plants m^{-2} [37–39]. Advantages of a higher planting density include a higher yield in the first 2–5 years, but as this yield increase does not compensate for higher planting costs, a density of one plant per square metre is recommended. Mechanical propagation may result in a variable degree of emergence (around 70%), but this does not seem to be a problem since stand density levels out after a few years [40]. In general, irrigation of newly planted miscanthus during the first growing season improves establishment rates.

4.1.3. Overwintering

On some sites in Denmark, Ireland and Germany, the rhizomes of the new stands did not survive the first winter after planting [8,41]. The high risk of winter losses is the main obstacle for the production of *M. x giganteus* in northern Europe. *M. sinensis* genotypes have superior survival rates to *M. x giganteus* [27,28]. The higher frost resistance of rhizomes from *M. sinensis* genotypes compared to *M. x giganteus* is accompanied by lower concentrations of water and reduced sugars and higher concentrations of starch [27]. An artificial freezing test in Germany showed that *M. x giganteus* rhizomes removed from the field in January are killed at temperatures below $-3.5^\circ C$ [27]. At northern sites, soil temperatures at 5 cm depth often drop below $-4^\circ C$; partly explaining the high losses of newly established trials.

Agronomic methods as well as genetic improvements in frost tolerance by breeding may also be used to improve over-wintering in the establishment year. A long first growing season is seen as essential for sufficient development to have occurred before the plants face winter conditions. Micro-propagated *M. x giganteus* plants have been observed to have lower winter survival than rhizome propagated plants [13,28].

Similar results were obtained by Schwarz et al. [31], who also found that micro-propagated plantlets were more sensitive to sub-optimal conditions (e.g. summer drought). In general, irrigation of newly planted rhizomes or plantlets improves establishment rates under drier conditions. Increased over-winter survival and establishment rates in macro-propagated crops have been reported when larger rhizome pieces are more deeply planted or a covering with straw or cover crops are used [31].

4.2. Fertilization

Field trials at different locations in Austria, Germany and Greece showed no significant response of *M. x giganteus* to N fertilizer from the second or third year onwards [19,41–45]. An amount of 60 kg ha^{-1} N was found optimal to support the development of the rhizome system [46]. The low fertilizer demand is largely attributable to the translocation of the nutrients to the rhizomes at the end of the growing season. It has been estimated that translocation from the shoots to the rhizomes accounts for 21–46% of N, 36–50% of P, 14–30% of K and 27% of Mg [43].

Neukirchen [47] showed that at the end of winter the rhizomes of 6-year old German *Miscanthus* stands contain 265 kg N and 235 kg K ha^{-1}. In spring, these reserves are mobilized to be brought back into the new shoots, making miscanthus partly independent of the actual N supply from the soil [48].

Experiments with the isotope ^{15}N showed that only 38% of $^{15}NH_4$ $^{15}NO_3$ supplied at 60 kg ha^{-1} N was taken up by the plant, of which over half was found in the rhizomes [48]. The greatest part of the N found in the plant came not from fertilizer but from soil mineralization and deposition. It may be concluded that N fertilization is necessary mainly on soils with low N contents. At locations with sufficient N mineralization from soil organic matter, no effect of N fertilization on yield is observed. To meet N requirements, 50–70 kg ha^{-1} $year^{-1}$ nitrogen may be given at the onset of sprouting from the rhizomes.

Although the potassium requirement of miscanthus is about 4–8 kg t^{-1} of dry matter, K fertilization did not improve the yield of *M. x giganteus* [49] which may be an effect of the good K supply level in the soil. Overall nutrient requirements for N, P and Ca are about 2–5, 0.3–1.1 and 0.8–1.0 kg t^{-1} of dry matter.

4.3. Crop protection

In the year of planting, miscanthus, competes poorly with weeds, so weed control is needed, either mechanical or chemical. In tests of different herbicides, it was found that those suitable for use on maize or other cereals can be used on *M. x giganteus* [50]. Once the crop is well established (from year two or three onwards), weed control is no longer necessary [51].

To date, there are no reports of plant diseases significantly limiting production, but the crop is known to be susceptible to *Fusarium* [52], to Barley Yellow Dwarf Luteovirus [53] and to miscanthus blight (*Leptosphaeria* sp.) [54].

5. Yield potential

The full establishment of a miscanthus stand takes 3–5 years [45,46], during which time the yield increases in each successive year. In addition, yield varies according to the date and method of harvest and these are discussed in the sections below.

Yields reported for trials all over Europe are presented along with some information on management conditions (Table 1). Yields of up to 25 t ha^{-1} $year^{-1}$ (dry matter) have been obtained from the third year onwards in the spring harvest for *M. x giganteus* crops between the latitudes 37 N (Southern Italy) and 50 N (central Germany). However, there have been huge differences in biomass yields from 2 t ha^{-1} [55] to 44 t ha^{-1} [56] (Table 1).

Genotypes differ considerably in their yield potential [25,26,55]. *M. sinensis* genotypes which have been bred for ornamental purposes are mostly inferior to *M. x giganteus* [55]. In more northern, cooler regions, such as Denmark, *M. sinensis* genotypes from Japan can reach similar yields to *M. x giganteus* [26]. In southern and central Europe *M. x giganteus* is the most productive genotype [25].

Yield above 30 t ha^{-1} (dry matter) are reported for locations in southern Europe with high annual incident global radiation and high average temperatures (e.g. 6200 MJ m^{-2} and 15.4°C; data for southern Portugal) but only with irrigation. In central and northern Europe (from Austria to Denmark) where global radiation and average temperatures are lower (e.g. 3500–3900 MJ m^{-2} and 7.3–8.0°C; data from

Table 2
Mineral and carbohydrate content of miscanthus samples harvested at two dates in the Netherlands

Mineral content (% dry matter)	Harvest date	
	19 November 97	29 January 98
N	0.47	0.36
P	0.06	0.00
K	1.22	0.96
Cl	0.56	0.09
Sugars	0.30	2.07
Starch	0.70	0.14

Denmark and Germany), yields without irrigation are more typically 10–25 t ha^{-1} (dry matter). Yield variation in central Europe is probably mainly caused by soil type and soil water availability. Although stands are easier to establish on lighter soils, in the long run yields are higher on heavy soils [45]. This is explained mainly by the improved water availability in heavy soils.

6. Harvest and storage

Harvesting can commence when the crop has senesced, which is determined by minimum temperatures in colder climates. The later that the harvest can be performed, the lower are both the moisture content and the mineral content (both of which are desirable); however, there is a trade-off, since the biomass yield decreases as well. Table 2 shows an example of the decrease in mineral contents between November and January. In Germany and the Netherlands, moisture content has been shown to decrease from 70% (fresh weight basis) in November to 20% or less by March or April [57,58]. Depending on the weather conditions, most drying normally takes place in spring.

During winter, most of the leaves and the non-woody tops fall off the miscanthus plant. The extent of these losses ranges from 3–25% by December to 15–25% by March [57]. In the Netherlands losses of between 29 and 42% were recorded for the period from 1 October to March, but these varied greatly with the weather conditions between individual years and locations (Fig. 2). Average losses shown here are about 35.5%. According to Kath-Petersen [57], actual harvest losses are about 25%, while the stubble remaining in the field represents a further loss of 17%. Thus the total pre-harvest and harvest losses may amount to as much as 67% of the biomass available before winter.

Harvest is usually carried out in spring (February to April), in order to collect well-dried material (Fig. 3). However, the optimal time for harvesting may be quite short, since the crop will be about to re-start growth in April, and this can add to the costs of harvest. To lengthen the harvesting period, the crop may be harvested wet and then dried artificially or ensiled [58].

6.1. Harvest methods

So far, only existing equipment has been used for harvesting miscanthus. In order to harvest larger areas, machinery will need to be adapted to the typical height (2.5–3.5 m) and stiffness of the miscanthus crop [33,59]. Multi-phase harvest methods consist of mowing, followed by swathing, picking up and baling or bundling, or chopping with or without further compaction. Multi-phase methods permit drying of the crop in a swath, which is faster than drying of the standing crop due to the high humidity of the microclimate at ground level. In single-phase harvest methods, mowing and the subsequent treatments are combined in one machine. This saves labor time and losses incurred in picking-up. Under normal soil conditions, multiple passes of machines will not decrease yields due to soil compaction as long as the contact pressure of the tyres is less than 2 bar (200 kPa) [57].

Standard mowing machines for grain or grass do not work well with the tall, stiff stems of miscanthus, although rotary mowers can be adapted to do the job [8]. The "Kemper" mowing attachment for forage harvesters (maize silage choppers) works well, although the cutting height has to be rather high to avoid jamming [58]. The mowing attachment needs to be row-independent, since in older stands of miscanthus the original planting pattern is no longer distinct. The miscanthus plant tolerates a low cutting height, so a special mowing device needs to be designed to reduce harvest losses. Picking up from a swath can also result in losses when the stubble length is high.

Baling of miscanthus is possible using all kinds of balers. Round bales will give a baled dry matter density of about 130 kg m^{-3}, and rectangular "big bales" are about 150 kg m^{-3} [60,61]. Harms

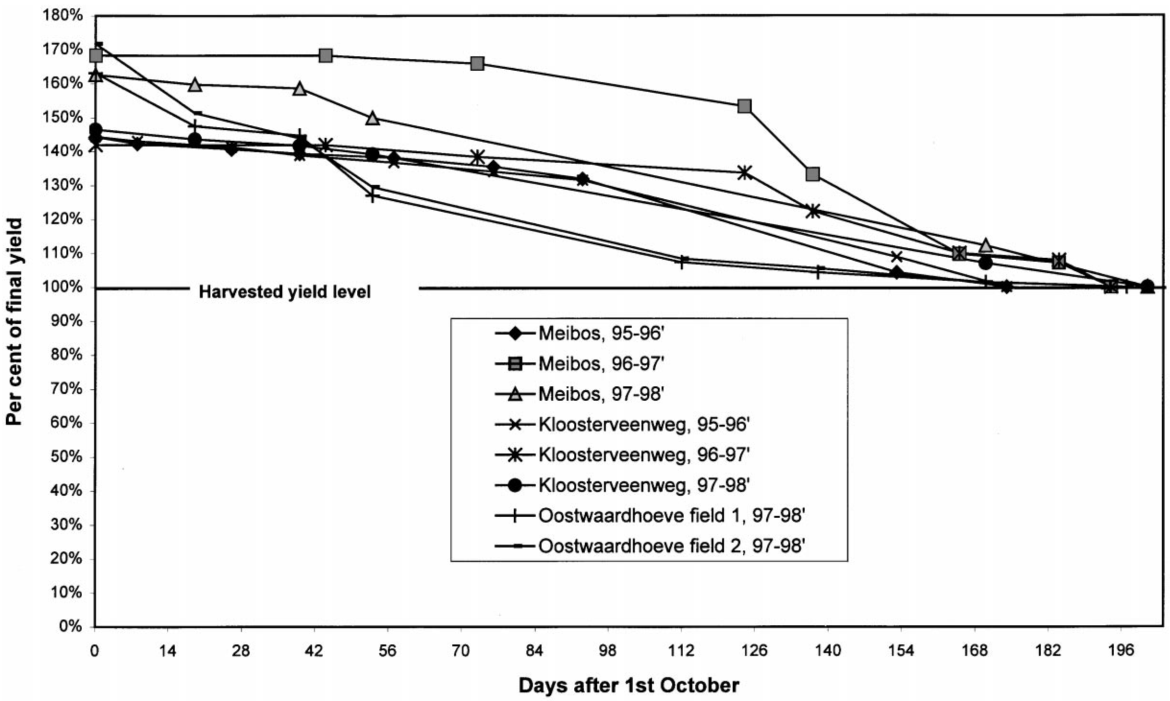

Fig. 2. Decrease in the harvestable amount of Miscanthus over the course of the year, expressed in terms of the final yield harvested in April, for various years and locations in The Netherlands.

Fig. 3. 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.

[62] also describes a prototype "Compactroller", developed in Germany, which can reach a density of 300–350 kg m^{-3}.

Chopping can be performed with forage harvesters. The density in storage depends on the chopping length. At 11 mm and 44 mm length, the dry matter density is 95 and 70 kg m^{-3}, respectively. Mechanical compaction can increase this figure to 130 kg m^{-3}. Chopped miscanthus can be further compacted, if required; for example, a stationary paper-recycling baler gave a density of 265 kg m^{-3} [63]. In tests with a prototype mobile pelleting machine for plant biomass, bulk density ranged from 350 to 500 kg m^{-3} [64].

If whole stems are required for further processing into building materials or geotextiles, the principles of harvesting machines for reed grass or whole willow stems may be applied [63]. However, adaptation of these machines for the long, stiff and smooth miscanthus stems is essential in order to reach sufficient capacities.

Costs of harvesting depend very much upon the chosen methods and associated labor costs. The chosen methods also define the costs for subsequent storage and transport, since density varies with the harvest method, so it is only possible to compare complete production cycles or "chains" (Section 9).

6.2. Storage

Standard methods for straw or hay can be used for collecting and handling miscanthus bales for transport and storage. However, the shape of miscanthus bales tends to be more round and irregular. For handling of chopped material, methods similar to those for maize silage can be applied. For long-term dry storage the moisture content should be 15% or less [58]. At higher moisture contents, mould can build up, although some degree of natural ventilation will prevent this at moisture contents up to about 25%. Spontaneous heating in storage can be controlled as long as some ventilation is allowed, since airflow resistance in both bales and piles of chopped material is low [65].

Storage may be under roof, tarpaulin or plastic sheeting, or can be without cover. Storage under roof requires the highest investment, but it saves on labor for placing and controlling sheeting as well as possibility of water leaks and consequent loss of quality and quantity. It is also difficult to maintain sheeting in good condition under windy conditions [8]. Large piles of chopped material can be left uncovered, accepting the loss of the outer layers which will absorb moisture in 5–50 cm depth. Preliminary tests with coverage of combustible waste biomass such as sawdust, chicken manure, steamed potato peel and roadside hay showed hopeful results. However, a thorough cost comparison for all the given storage systems is not yet available. Material costs in the Netherlands, estimated by [66] were 1.6 Euro t^{-1} (US\$1.50 t^{-1}) and 17.6 Euro t^{-1} (US\$16 t^{-1}) (dry matter) for chopped miscanthus under plastic sheeting and a new building, respectively. For baled miscanthus, the estimates were 3.3 Euro t^{-1} (US\$3 t^{-1}) and 8.1 Euro t^{-1} (US\$7.50 t^{-1}), respectively. These costs include both maintenance labor and capital depreciation over the lifetime of the building.

6.3. Drying

If full drying in the field is not possible, additional drying will be required immediately after harvest (if moisture content is above 25%), or during storage (if moisture content is below 25%) if ventilation is established. Kristensen [67] found that in a natural ventilated pile of chopped miscanthus in Denmark, in 187 days the moisture content decreased from 63 to 51%, while the recorded dry matter losses were 5.4%. Kristensen [68] also found that when chopped miscanthus with a moisture content of 59% was ventilated at a rate of 21,500 m^3 h^{-1} ambient air, the moisture content has dropped to 17.5% after 91 h. According to Zaussinger and Dissemond [69] the airspeed for drying should be at least 0.1 m s^{-1}. A 4 m layer of chopped miscanthus could thus be dried in 3 days from 25 to 15% moisture content at an air temperature of 20°C. If no self-heating occurs, losses will be modest. Tack and Kirschbaum [65] reported losses of 4–6% in a test where bales with a moisture content of 50% were ventilated with unheated air and biomass temperatures were below 20°C.

In the Netherlands, bales with a moisture content around 25% were stored in a stack outdoors, covered by tarpaulin with some space left between most of the bales. After one summer and winter the moisture content had dropped to about 12%. Costs of drying with ventilated ambient air were relatively low, up to 15 Euro t^{-1} (US\$14 t^{-1}) dry matter for material harvested in January [70].

For industrial drying a range of devices can be used, but there are no reports available from controlled tests. Van den Heuvel [71] estimated energy costs of 3.7, 12.0 and 31.2 Euro t^{-1} (US\$3-28 t^{-1}) (dry matter), respectively, for theoretical drying to a moisture content of 15% from initial values of 30, 50 and 70% moisture.

6.4. Ensiling

Miscanthus can be stored under anaerobic conditions, e.g. by sealing a pile of chopped material under plastic sheeting. Sufficient sugar is available in miscanthus for the subsequent production of sufficient lactic acid to kill most microbiological activity [58]. It is best to remove as much air as possible by compaction before covering the pile, e.g. by driving tractors over it. The pH will decrease in 2 weeks to 4.2 if the material has a moisture content of 60%. With lower moisture contents the pH will remain higher, but the conservation of the pile is just as effective. No inoculation with bacteria is required in practice,

Table 3
Miscanthus fuel properties reported for Europe

Country	Austria	Germany	Germany	Germany	Denmark	Denmark	Greece
Genotype	*M. x giganteus*	*M. x giganteus*	*M. x giganteus*	*M. x giganteus*	*M. x giganteus*	*M. sinensis*	*M. x giganteus*
Age of stand	3 years	3 years	3 years	3 years	3–5 years	3–5 years	2–3 years
Month of harvest	January/February	February/March	February	February/March	January–April	January–April	End of growing season
Water content (% fresh weight)	30	20–40	16–28		23–62	21–48	38–44
Ash (% dry matter)	2.79	3.26–3.59	1.62–4.02				1.60
N (% dry matter)	0.49	0.54–0.60	0.19–0.39	0.19–0.62	0.55–0.66	0.58–0.67	0.33
P (% dry matter)		0.06–0.08		0.04–0.11			
K (% dry matter)		1.17–1.28	0.52–0.94	0.52–1.21	0.60–1.03	0.31–0.48	
Ca (% dry matter)		0.08	0.09–0.14	0.05–0.14			
Mg (% dry matter)		0.06–0.07		0.02–0.06			
S (% dry matter)	0.04		0.07–0.10	0.08–0.19			
Cl (% dry matter)	0.24		0.10–0.17		0.18–0.50	0.04–0.12	
C (% dry matter)	48.3		47.8–49.7	48.2–48.8			
H (% dry matter)	5.46		5.64–5.92				
O (% dry matter)			41.4–42.9				
Heating value (MJ kg^{-1})	19.12 (H_o)	18.1–19.2	17.05–18.54 (H_u)				
Reference	[75]	[19]	[49]	[76]	[26]	[26]	[42]

and much of the methodology for ensiling is the same as for chopped silage maize. Ensiling bales by an air-tight plastic covering is hard to achieve because of the sharp hard stems sticking out. If used for combustion, the moisture content can be decreased by drying with waste heat from the combustion plant, but a screw press may also be used — a decrease from 55 to 40% can be achieved easily. Mineral content is also reduced by this process.

7. Combustion characteristics

The chemical composition of miscanthus biomass is favorable for combustion. The mineral content is low compared with wheat straw, but higher than for willow/poplar coppice. Mineral concentrations are reported to be low at the time of the early spring harvest: 0.2–0.6% N; 0.5–1.3% K; 0.1–0.5% Cl and 1.6–4.0% ash (see Table 3). Like other biomass fuels, reactivity and ignition stability are high compared with coal.

The composition of miscanthus ash includes approximately 25–40% SiO_2, 20–25% K_2O, 5% P_2O_5, 5% CaO and 5% MgO — a range of values is reported from different studies (e.g. [72,73]). Miscanthus ash contains higher amounts of nutrients and lower amounts of heavy metals than native wood ashes [74]. The main problem of combustion of miscanthus biomass is the low ash melting point. 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 [73]. However, other results show miscanthus can have a higher ash softening temperature than straw [68].

Biomass characteristics can vary considerably from year to year and between different locations [49]. The influence of crop management measures like fertilization is negligible compared to the differences between sites [7,75]. However, increased N fertilization can lead to slight increases in N, K and water content [3,37]. Changes in the quality of miscanthus biomass in the first year after establishment can partly be explained by early developmental physiology of the crop. Concentrations of N and K decrease with age during the establishment period [76].

Weather conditions have a strong influence on biomass quality. Following senescence, Cl, K and ash components are leached from the shoots [49,77], but the composition of leaves and stems are different [49,78]. Leaf losses over winter therefore vary the quality of the harvested biomass, with the amount of losses increasing with strong winds. On the other hand, wind contributes to the drying-out of the biomass [19]. Under wet conditions, the pliable biomass is prone to losses by breaking of shoot tips, especially under snow and ice, and heavy snow can lead to severe lodging.

Soil conditions have been reported to influence biomass quality, especially ash content, in *Phalaris arundinacea* [79]. However, results from similar studies on miscanthus have yet to be published. Overall, a delayed harvest appears to be the most important management tool to improve biomass quality in miscanthus.

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 [80]. When combusted in a batch stoker the combustion of Miscanthus was steadier and cleaner (lower emissions of solids) than if straw was used [68].

8. Energy balance and other environmental considerations

8.1. Energy and CO_2 balance

In an analysis by Lewandowski et al. [81], a yield of 20 t ha^{-1} (dry matter) was assumed. Energy inputs were 1251 MJ t^{-1}, and 112 kg CO_2 emissions per tonne dry matter were estimated for the production, harvest, transport and milling of the biomass, before it was burned in a pulverized fuel combustor. Assuming that 100 kg ha^{-1} N was applied yearly, 23% of the CO_2 emissions ($374\,MJ\,t^{-1}$) were due to the input of nitrogen fertilizer. Seventeen percent of the CO_2 emissions ($324\,MJ\,t^{-1}$) were spent on fuel processing, i.e. pulverization. Overall, 5–7% of the harvested energy (lower heating value) is needed for production and processing [81,82], giving an output : input ratio of between 14 : 1 and 20 : 1 [83]. In another example (small-scale heat and power co-generation with fluidized-bed gasification/gas turbine technology), the energy balance was 9.6 : 1 [84]. N_2O emissions from normal levels of N-fertilizer application had only a modest effect on net offsets of greenhouse gas warming potential (6% of total CO_2 displacement) [82].

8.2. Other emissions

Although the use of miscanthus biomass as solid fuel can avoid greenhouse gas emissions [82,83,85], both the production of miscanthus and its use may cause a range of environmentally harmful emissions. Major concern lies in the effects on water and soil. Christian and Riche [86] showed that nitrate leaching occurs mainly in the year of planting. This is also true for erosion because the plants remain small in the first year, take up little nitrogen and do not provide full ground cover. From the third year onwards, reported leaching of 3–30 $kg\,ha^{-1}$ N (without N fertilizer, and with application of 120 $kg\,ha^{-1}$ N) is close to those values recorded under extensively managed grassland [86].

As there is little need to guard against pests and diseases, and weed control is limited to the first two years, a low pesticide requirement can be expected, together with a low risk of release of pesticides into the environment.

8.3. Soil fertility

Due to the long period of soil cover and the high inputs of organic matter from shed leaves of miscanthus, it can be expected that soil organic matter will increase and soil structure improve under miscanthus cultivation, compared with other arable crops. An established stand accumulates 10–20 t dry matter per hectare of rhizomes in the top soil of 25 cm, and an additional 6–8 t roots [37]. The humus content of the soil in a 4–8 year old miscanthus stand increased along with the cation exchange capacity and a slight increase of water retention occurred [37]. A dense root mat has developed by years 2–3, which may prevent leaching of nitrogen (see above). The maximum root density at this time is found at a depth of 0–40 cm [87], although some roots penetrate down to 250 cm and deeper [88]. There are some concerns that miscanthus production may, therefore, prevent ground water restoration and diminish groundwater [37].

8.4. Landscape, flora and fauna

As a new crop in the landscape, miscanthus, which can attain a height of up to 4 m under European conditions, may have a significant visual impact — especially, when fields remain unharvested until February. On the other hand, tall stands of miscanthus can serve as cover and habitat for birds and mammals [89]. According to Jodl et al. [90], miscanthus stands contain more large animals (mammals, birds) than other herbaceous crops (maize or reeds), possibly due to the greater diversity of canopy structure leading to a higher number and greater range of ecological niches. However, whereas the number of insect species increased compared to other herbaceous crops, the number of individuals in miscanthus stands showed a decrease [89]. This may be partly explained by the low digestibility of miscanthus organic matter [89].

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, USA, which have caused local concern, and reinforce the case for releasing only sterile miscanthus hybrids [91].

9. Economics

As may be concluded from the preceding information, the economics of miscanthus depend very much upon a number of assumptions: the yield, the chosen production “chain”, the propagation method, the number of years of assumed production, whether costs are annualized or not, transport and land-use costs, and the farmer's own profit margin. Note that the cost of land is often not included when comparisons are made, for example, with woody biomass production from short-rotation forestry.

Huisman et al. [63] calculated the total costs of various production chains and scenarios, using a crop model for optimizing methods of harvesting, storage and transport. The following results make certain assumptions: a 15 year production period, a 72 km (45 mile) round trip for transport to the processing plant, an average yield of 12 t ha^{-1} (dry matter), harvesting carried out by a contractor, no drying costs included, costs of land use of 725 Euro ha^{-1} (US$267 $acre^{-1}$), and zero profit margin. In addition, it was assumed that the rhizomes used for establishment were produced at the farm itself, and that costs are annualized at an interest rate of 7%. The total of pre-harvest production costs and grubbing-up costs after 15 years amount to 26 Euro t^{-1} (US$24 t^{-1}) (dry matter). Total costs including harvest, storage, transport to the processing plant and chopping at the plant (if not done previously), are given below for various harvest methods, including the pre-harvest costs above:

- self-propelled forage chopper: 66.6 Euro t^{-1},
- self-propelled forage chopper (after storage, harvested material is compacted before transport by mobile baler): 62.6 Euro t^{-1},
- self-propelled (big) baler: 66.4 Euro t^{-1},
- compact roll baler: 73.5 Euro t^{-1},
- whole stem harvester: 102.4 Euro t^{-1}.

All data are on a dry matter basis; the last two figures are estimates for machines not yet commercially available.

Earlier economic analysis based upon Danish conditions also suggested that miscanthus production costs are comparable to other annual and perennial energy crops — about 70 Euro t^{-1} (US$64 t^{-1}) or 4.1 Euro GJ^{-1} (US$3.70 GJ^{-1}) — making the crop marginally economically viable if agricultural set-aside payments are included. The market price of straw is about 80 Euro t^{-1} (US$73 t^{-1}) in Denmark; in contrast the price of wood chips in Sweden is as low as 32 Euro t^{-1} (US$29 t^{-1}). However, a 10–12 year rotation (growing cycle) is required to absorb establishment costs [29].

10. Prospects for miscanthus production in North America

The sustained European interest in miscanthus suggests that this novel energy crop deserves serious investigation as a possible candidate biofuel crop in North America and elsewhere, perhaps alongside switchgrass. No agronomic trials or trial results for miscanthus are yet known from the conterminous USA, so its performance under US conditions is virtually unknown [92]. Limited experience has been gained by the US Department of Agriculture/Natural Resource Conservation Service (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 [91]. Small-scale Canadian trials of *Miscanthus x giganteus* began in 1997–1998 outside Montreal (latitude 42.5°N), with initial annual yields at spring harvest of 10–11 t ha^{-1} dry weight [93].

Speculating from European data on small plots in agricultural experimental stations, the crop may attain as much as 20–35 t ha^{-1} (8–14 t $acre^{-1}$ dry weight) by the end of the growing season, but it is usually harvested in early Spring, after nutrient recycling and drying has taken place — by which time the harvestable yield has reduced to about 13–24 t ha^{-1} (5–10 t $acre^{-1}$ dry weight). The European conditions for these trials range from latitude 37 to 50°N (roughly from Kentucky, USA, to the Canadian border, although it should be noted that the European climate is generally warmer and more moderate than for North America at the same latitude). Average annual temperatures and rainfall for the European trials range from 7.5 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. Costs are expected to fall and uncertainties to be reduced as first demonstration trials and then commercial planting 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.

11. Note on currency conversion

Although costs determined in Euros have been given also as the equivalent in US dollars (at the exchange rate of Euro 0.91/US$1.00 for May 2000), the authors note that this exchange rate has varied over the range 0.89–1.17 during the writing of this paper, so exact cost comparisons in US dollars are difficult. Note also that many European currencies have a fixed exchange rate to the Euro, so that prices in Euros reflect actual costs incurred in local currency.

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