BIOFUELS

Environment and Harvest Time Affects the Combustion Qualities of *Miscanthus* Genotypes

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ABSTRACT

***Miscanthus* spp. are high-yielding perennial C_4 grasses, native to Asia, that are being investigated in Europe as potential biofuels. Production of economically viable solid biofuel must combine high biomass yields with good combustion qualities. Good biomass combustion quality depends on minimizing moisture, ash, K, chloride, N, and S. To this end, field trials at five sites in Europe from Sweden to Portugal were planted with 15 different genotypes including *M.* × *giganteus*, *M. sacchariflorus*, *M. sinensis*, and newly bred *M. sinensis* hybrids. Yield and combustion quality at an autumn and a late winter/early spring harvest were determined in the third year after planting when the stands had reached maturity. As expected, delaying the harvest by three to four months improved the combustion quality of all genotypes by reducing ash (from 40 to 25 g kg^{-1} dry matter), K (from 9 to 4 g kg^{-1} dry matter), chloride (from 4 to 1 g kg^{-1} dry matter), N (from 5 to 4 g kg^{-1} dry matter), and moisture (from 564 to 291 g kg^{-1} fresh matter). However, the delayed harvest also decreased mean biomass yields from 17 to 14 t ha^{-1}. There is a strong interaction among yield, quality, and site growing conditions. Results show that in northern regions of Europe, *M. sinensis* hybrids can be recommended for high yields (yielding up to 25 t ha^{-1}), but *M. sinensis* (nonhybrid) genotypes have higher combustion qualities. In mid- and south Europe, *M.* × *giganteus* (yielding up to 38 t ha^{-1}) or specific high-yielding *M. sinensis* hybrids (yielding up to 41 t ha^{-1}) are more suitable for biofuel production.**

THE PERENNIAL C_4 grass *Miscanthus* sp. combines several properties that make it a promising crop for the production of solid biofuel feedstock. It has a high yield potential and is an environmentally benign crop that can be grown with very low pesticide and fertilizer inputs (Lewandowski et al., 2000). Production of economically viable solid biofuel from *Miscanthus* spp. must combine both high biomass yields and good combustion qualities. Good biomass combustion quality depends largely on minimizing moisture, ash, K, chloride, N, and S.

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Published in Agron. J. 95:1274–1280 (2003).

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The reasons for these requirements can be summarized as follows. Biomass with moisture contents below 200 to 250 g kg^{-1} fresh matter can be stored safely without the danger of self ignition (Clausen, 1994) and burns more efficiently while ash lowers the heating value of the biomass and causes slagging of the boiler heat exchangers (Hartmann et al., 1999). High levels of K are undesirable because it decreases the ash melting point, but critical levels will depend on combustion technique. Chloride can lead to corrosion through reaction with water to form HCl or with K to form gaseous KCl, both of which are corrosive and reduce boiler life (Baumbach et al., 1997). Furthermore, high chloride concentrations can lead to emissions of dioxine and furane (Siegle and Spliethoff, 1999). Nitrogen concentrations in biofuels need to be as low as possible to minimize fertilizer off-takes and to reduce emissions of NO_x during combustion. To avoid SO_2 emissions, biomass S concentrations also need to be as low as possible.

To date, most research on *Miscanthus* sp. as an energy crop has concentrated on maximizing the yield of a vigorous clone known as *M.* × *giganteus* in different climates. Although recent papers have also described trials with a range of *Miscanthus* genotypes (Eppel-Hotz et al., 1998), only one attempt has been made to study the quality of the biomass of different genotypes for combustion (Jørgensen, 1997). This work demonstrated the importance of delayed harvest time and the antagonism between yield and quality for three genotypes at one site in Denmark. In the present paper, we extend this preliminary work by investigating the key characteristics relevant for biofuel combustion in 15 *Miscanthus* genotypes, some of them newly bred hybrids, grown at five sites in Europe.

MATERIALS AND METHODS

Field Trials

The origins of the 15 genotypes have already been described in Clifton-Brown et al. (2001b). Briefly, of the 15 *Miscanthus* genotypes selected, there were four acquisitions of *M.* × *giganteus* (No. 1–4), one *M. sacchariflorus* (No. 5), five hybrids from crosses with *M. sinensis* and *M. sacchariflorus* (No. 6–10), and five wild *M. sinensis* (nonhybrid) genotypes (No. 11–15). These genotypes exhibit a range of characteristics, including differences in flowering time and senescence rate.

All genotypes were micropropagated by explants to ensure genetic uniformity and planted at five sites in Sweden, Denmark, England, Germany, and Portugal in spring 1997 at a density of 2 plants m^{-2}. The trial was a randomized block trial

Table 1. Site characteristics for the European locations of the field trials. Soil types are described according to USDA nomenclature, and total elemental concentrations were determined. Crop growing conditions in 1999 are generalized by mean air temperature and total rainfall (+ irrigation) between April and September. Harvest dates following the 1999 growing season are shown in conjunction with the period (days) between harvests, the total rainfall, and the minimum air temperature.

		Soil		Soil analysis				Growing season (Apr.–Sept. 1999)			Harvest date		Period between harvests		
Country	Lat, long	Type	pH	N	P	K	C	Air	Rain	Irrig.	Autumn	Winter	Days	Rain	Air min
				g kg^{-1}				°C	mm					mm	°C
Sweden	55°60′ N, 14°00′ E	Aeric Endoaquept	6.7	0.7	0.074	0.069	18	13.8	416	0	18 Oct. 1999	7 Feb. 2000	112	219	−15.9
Denmark	56°30′ N, 09°35′ E	Typic Fragiudalf	5.9	0.7	0.028	0.072	11	13	409	0	18 Oct. 1999	14 Feb. 2000	118	221	−11.5
England	51°48′ N, 00°21′ W	Aquic Paleudalf	6.9	0.7	0.009	0.097	8	14.4	364	0	3 Nov. 1999	28 Jan. 2000	88	152	−5
Germany	48°40′ N, 09°00′ E	Vertic Eutrudept	7.4	1.1	0.063	0.195	16	14.9	410	0	21 Nov. 1999	2 Feb. 2000	71	191	−17.8
Portugal	38°32′ N, 09°13′ W	Aquic Xerofluvent	6.4	0.4	0.038	0.042	5	20.2	147	496	6 Oct. 1999	10 Jan. 2000	96	190	−3.1

with three replications (except Portugal). Plot size was 7 by 7 m. Representative soil samples were taken to a depth of 90 cm. Observations and measurements reported here are from the third growing season (1999) because previous studies have shown *Miscanthus* spp. stands have by then reached ceiling yields. Irrigation was only used at the Portuguese site (see Table 1).

Within the growing season, start of flowering, stem density, and leaf greenness were monitored. Determination of autumn *greenness* (an indication of senescence) is described in Clifton-Brown et al. (2001b). Each autumn, a sample of 2-m^2 ground area was harvested from within the central plot area (avoiding border effects) to assess the total aboveground productivity. Another sample of at least 2 m^2 was harvested in late winter/early spring (dates in Table 1). Cutting height of the stems was 5 cm above ground. Moisture concentration of a subsample was determined after drying at 80°C until constant weight, and dry matter yield was calculated at each harvest. The proportion of leaf dry weight to total yield was assessed from the shoots of one plant by separating the leaf lamina at the ligule from the stem.

Chemical Analysis

Before chemical analysis, the dried subsamples used for determination of moisture content were milled through a 1-mm sieve. The samples from all locations were collected and analyzed by the same laboratory. Samples were analyzed for ash, K, Cl, N, and S concentrations. Ash concentrations were determined by loss on ignition at 550°C. The N concentrations of the plant and the soil samples were analyzed using the Dumas method (LECO, St. Joseph, MI). For the determination of K and S concentrations, 500-mg plant samples were digested with 4 mL of nitric acid and 1 mL of hydrogen peroxide in closed PTFE vessels in a pressurized microwave digestion system (MLS 1200, MLS GmbH, Leutkirch, Germany), and K and S were determined in digests by inductively coupled plasma optical emission spectrometry (ICP-OES, Leeman PS1000, Leeman Labs, Hudson, NH). The National Institute of Standards and Technology (NIST) Standard Reference Material 1575 (Pine Needles) was used for quality control. Chloride was extracted with boiling water (VDLUFA, 1996) and determined by ion chromatography.

Phosphorus and K concentrations of the soil were analyzed according to methods described in VDLUFA (1997). The C concentration in the soil was determined by nondispersive infrared (NDIR) gas analyzer spectroscopy (VDLUFA, 1997).

Statistical Analysis

When data were normally distributed, analysis of variance (ANOVA) was used to determine significant differences. Interactions among location, genotype, and harvest time are presented with the mean squares. For multiple comparisons between genotypes within each country and harvest, the minimum significant difference (MSD) at $P = 0.05$ was calculated from the Tukey test. All statistics used the software Data Desk v4.1 (Data Description, Ithaca, NY).

RESULTS AND DISCUSSION

Autumn yields over the 3 yr following establishment for all 15 *Miscanthus* genotypes at five locations in Europe were presented in Clifton-Brown et al. (2001b) where it was shown that yield increased each year for the first 3 yr except where a genotype failed to overwinter. As reported in Clifton-Brown et al. (2001b), *M.* × *giganteus* and *M. sacchariflorus* did not survive the first winter in Denmark and Sweden; therefore, no data are presented for these genotypes at these locations. Differences between genotypes in overwintering characteristics are discussed in detail in Clifton-Brown and Lewandowski (2000). In climates where *M.* × *giganteus* survives the winter, stands normally reach ceiling yields for that site within three growing seasons when the planting density is >2 plants m^{-2} and weeds are controlled (Clifton-Brown et al., 2001c). In this paper, we present biomass yield and quality data for two harvests made following the third growing season: one in autumn at the end of the growing season when aboveground biomass is at its peak and a second delayed harvest in late winter/early spring when the crop has had time to ripen.

Delayed Harvest and Yield

Delayed harvest resulted in a mean yield reduction of 35% (from 17 to 14 t ha^{-1} dry matter) (Table 2). Yield losses decreased with the length of the period between the autumn and winter harvests. For example, the greatest yield losses were recorded in Sweden (average 53%) when there was a 112-d delay while the lowest losses were recorded in Germany (23%) where harvesting times were only separated by 71 d. Similar observa-

Table 2. Autumn and winter yields of 15 *Miscanthus* genotypes grown at five locations in Europe in the third growing season following planting. The four genotype groups were *M.* × *giganteus* (Gig), *M. sacchariflorus* (Sac), *M. sinensis* hybrids (Sin-H), and naturally occurring diploid *M. sinensis* (Sin).

Genotype group	EMI no.†	Sweden		Denmark		England		Germany		Portugal	
		Autumn	Winter	Autumn	Winter	Autumn	Winter	Autumn	Winter	Autumn	Winter
		Dry matter yield, t ha^{-1}									
Gig	1					13.8	9.2	22.8	17.5	37.8	19.6
	2					16.8	12.7	24.3	19.5		
	3					18.7	12.2	25.7	19.5	36.8	26.4
	4					14.6	12.1	29.1	20.7	34.7	25.3
Sac	5			1.4	0.4	11.1	6.3	12.6	12.7	35.2	22.4
Sin-H	6	19.3	11.2	16.4	8.8	15.7	11.3	20.0	14.3	27.2	15.3
	7	11.0		10.4	6.0	17.7	12.3	17.0	9.4	40.9	31.9
	8	24.7	13.3	15.9	9.3	6.5	5.4	19.2	14.2	21.0	13.2
	9	14.2		0.9	0.5	15.8	12.8	10.3	5.9	26.3	18.5
	10	20.5	14.7	18.2	10.9	14.0	11.1	19.1	14.2	20.3	12.2
Sin	11	15.4	10.1	15.0	8.6	8.0	6.5	12.8	10.3	16.2	11.6
	12	15.3	8.4	12.4	6.8	7.0	5.5	10.9	9.6	16.3	14.2
	13	17.3	10.3	11.2	7.3	10.9	7.3	12.3	11.1	22.4	17.6
	14	13.8	8.8	9.9	8.1	4.6	3.1	10.4	8.9	20.0	14.6
	15	9.7	7.1	6.8	4.9	5.9	4.5	9.1	6.8	16.1	13.4
Mean		16.1	10.5	10.8	6.5	12.1	8.8	17.0	13.0	26.5	18.3
Tukey‡		10.2	5.7	5.9	2.5	7.4	3.3	15.3	7.6	18.0	12.5

† European *Miscanthus* Improvement project number.
‡ Tukey test applied to calculate the minimum significant difference between genotypes within a site and within a year at $P = 0.05$.

tions were made in a recent study in Ireland where *M.* × *giganteus* showed a steady reduction in the harvestable biomass after the first frost in autumn (Clifton-Brown et al., 2001a). These losses were mainly caused by leaf and upper-stem detachment. In a few exceptional cases where genotypes were growing poorly, yields in late winter were reduced to zero through detachment and lodging of the weak stems (*M. sinensis* hybrids no. 7 and 9 in Sweden, Table 2).

Biomass Quality

Delaying harvest time from autumn until late winter reduced moisture concentrations in all genotypes at all sites (Tables 3 and 4). As with harvestable yield, reduction in moisture was associated with the length of the period between autumn and winter harvest (Tables 1 and 4). In all countries, there was a positive correlation between winter harvest moisture concentration and greenness in autumn (see Table 8 in Clifton-Brown et al., 2001b). An extreme case is that of the *M. sinensis* hybrid no. 7, a very late-senescing genotype. In Portugal, this genotype had a moisture of 400 g kg^{-1} fresh matter, almost double that of the early senescing *M. sinensis* genotypes (no. 11–15). In most countries, the lowest moisture contents were measured in the biomass of the early flowering and senescing *M. sinensis* genotypes (Table 4).

Although delayed harvest in winter reduced moisture contents recorded in *M.* × *giganteus, M. sacchariflorus*, and most *M. sinensis* hybrids, these were still above the threshold of 250 g kg^{-1} fresh matter set by Clausen (1994) for safe storage of stalky biomass. There are several options to reduce the moisture content below this target: (i) harvest as late as possible, i.e., just before shoot emergence in spring; (ii) store the harvested biomass in bundles at the side of the field; or (iii) barn-dry with forced ventilation. All have associated costs in terms of yield reduction and handling (Huisman et al., 1997).

Ash, K, and Cl concentrations were significantly influenced by harvest time, site conditions, and genotype (Tables 3, 5, 6, and 7). Delayed harvest time reduced ash concentrations by a mean of 28% in Portugal and England and 42, 50, and 54% in Germany, Sweden, and Denmark, respectively. Previous studies have shown that leaves have higher ash concentrations than stems

Table 3. Statistical analysis using ANOVA for all countries, genotypes, and harvests. Mean squares (MSQ) and probability (*P*) are reported for each characteristic.

Source	df	Yield		Moisture		Ash		K		Cl		N		S		Leaf share	
		MSQ	*P*	MSQ	*P*	MSQ	*P*	MSQ	*P*	MSQ	*P*	MSQ	*P*	MSQ	*P*	MSQ	*P*
Country	4	2 959	***	558	***	181.8	***	4.14	***	7.8	***	1.12	***	0.0244	***	12 734	***
Genotype	14	1 318	***	1 706	***	13.7	***	3.50	***	0.9	***	0.28	***	0.0130	***	1 775	***
Country × genotype	46	775	***	606	***	26.2	***	1.20	***	0.3	***	0.35	***	0.0064	***	1 576	***
Harvest time	1	323	ns†	27 218	***	54.4	***	9.02	***	3.1	***	0.25	*	0.0030	**	1 646	***
Country × harvest time	4	21	ns	1 940	***	9.9	**	1.15	**	1.4	***	0.09	ns	0.0034	***	1 502	***
Genotype × harvest time	14	141	ns	611	***	11.2	***	0.67	**	0.3	***	0.17	***	0.0009	ns	99	ns
Country × genotype × harvest time	44	71	ns	394	***	5.0	***	0.45	**	0.2	***	0.07	ns	0.0016	***	386	***
Error	228	97		92		2.1		0.26		0.0		0.05		0.0006		96	

* Significant at the 0.05 level.
** Significant at the 0.01 level.
*** Significant at the 0.001 level.
† ns, not significant.

Table 4. Moisture concentration at autumn and winter harvests of 15 *Miscanthus* genotypes grown at five locations in Europe in the third growing season following planting. The four genotype groups were *M.* × *giganteus* (Gig), *M. sacchariflorus* (Sac), *M. sinensis* hybrids (Sin-H), and naturally occurring diploid *M. sinensis* (Sin).

Genotype group	EMI no.†	Sweden		Denmark		England		Germany		Portugal	
		Autumn	Winter	Autumn	Winter	Autumn	Winter	Autumn	Winter	Autumn	Winter
		Moisture, g kg^{-1} fresh weight									
Gig	1					601	408	513	425	486	373
	2					572	393	506	397		
	3					573	432	493	393	497	241
	4					599	370	510	411	507	287
Sac	5			645	303	592	347	554	362	536	329
Sin-H	6	567	215	660	257	520	338	521	395	538	302
	7	636		687	354	553	417	552	431	520	400
	8	544	264	571	283	571	258	581	424	491	191
	9	662		729	517	603	445	570	493	535	357
	10	608	266	588	307	510	279	517	310	547	218
Sin	11	598	216	609	225	471	209	550	231	557	244
	12	605	211	602	212	453	195	504	210	549	200
	13	611	253	641	245	452	256	530	260	565	258
	14	565	205	602	227	420	239	504	234	541	179
	15	545	196	631	244	424	260	528	227	636	161
Mean		594	228	633	289	528	323	529	347	536	267
Tukey‡		76	49	59	43	76	125	87	104	82	148

† European *Miscanthus* Improvement project number.
‡ Tukey test applied to calculate the minimum significant difference between genotypes within a site and within a year at $P = 0.05$.

(Lewandowski and Kicherer, 1997). Consequently, it was not surprising to observe that ash concentrations were associated with the proportion of harvested leaf material. Leaf share in the harvested biomass fell from 31 to 19% in the autumn and winter harvests, respectively. In Sweden, Denmark, England, and Germany, *M. sinensis* (no. 11–15) and *M. sacchariflorus* (no. 5) had the lowest ash concentrations. However, in Portugal, *M. sinensis* had higher ash concentrations than all other genotypes (except no. 8 and 10) because a new flush of shoots grew from the early flowering *M. sinensis* genotypes (no. 11–15) in late summer, and they did not senesce during the winter.

In the harvested plant material, large intersite variations in Cl concentrations were observed (Table 3, mean square = 7.8). Lowest Cl concentrations were found in biomass harvested in Germany (Table 7). In Sweden, Denmark, and England, K fertilizer was applied as KCl, and this probably led to the higher Cl concentrations in the biomass harvested at these sites (Wieck-Hansen, 1996) although in Portugal, high Cl concentrations were recorded in the biomass despite the fact that K fertilizer was applied as K_2SO_4. Here, irrigation water containing Cl was used for irrigation. Furthermore, Cl concentration may also be related to the proximity of the site to the sea because wind-born sea spray can deposit NaCl.

Nitrogen concentrations of the harvested biomass fell between autumn and winter (Tables 3 and 8) at all sites, and significant differences between the N concentrations of different *M. sinensis* hybrids were found (Table 8). However, no systematic variation between countries was observed that could indicate the occurrence of *low-N* hybrids, despite previous reports of an association between genotypes with lower leaf shares and lower N concentrations (Beuch and Boelke, 1996; Lewandowski and Kicherer, 1997). Translocation from

Table 5. Ash concentration at autumn and winter harvests of 15 *Miscanthus* genotypes grown at five locations in Europe in the third growing season following planting. The four genotype groups were *M.* × *giganteus* (Gig), *M. sacchariflorus* (Sac), *M. sinensis* hybrids (Sin-H), and naturally occurring diploid *M. sinensis* (Sin).

Genotype group	EMI no.†	Sweden		Denmark		England		Germany		Portugal	
		Autumn	Winter	Autumn	Winter	Autumn	Winter	Autumn	Winter	Autumn	Winter
		Ash, g kg^{-1} dry weight									
Gig	1					38.3	30.7	32.2	26.7	30.3	17.1
	2					36.9	28.9	31.7	24.9		
	3					38.3	30.1	28.0	24.7	33.2	18.5
	4					43.2	29.7	33.1	26.3	32.6	18.1
Sac	5			36.9	14.3	35.3	17.6	24.7	17.2	29.9	12.7
Sin-H	6	36.5	19.2	34.8	13.0	51.5	31.6	40.4	25.0	42.1	31.6
	7	39.7		41.0	22.1	41.4	37.2	38.3	23.6	42.0	28.3
	8	27.6	21.2	30.1	18.1	50.4	36.6	29.6	26.9	51.4	65.8
	9	37.2		52.0	26.7	42.1	38.0	41.2	26.1	35.9	30.7
	10	43.5	25.4	37.7	20.7	42.8	28.8	32.4	23.1	56.5	41.7
Sin	11	38.9	15.9	29.8	11.9	36.5	28.3	34.1	18.2	63.4	44.1
	12	46.8	19.7	33.3	13.5	40.4	30.3	35.8	19.5	66.8	49.4
	13	40.9	17.0	34.4	12.9	51.6	25.3	38.1	17.3	47.7	40.4
	14	42.5	18.3	34.0	14.5	51.7	39.7	35.0	22.0	69.3	49.3
	15	32.9	18.2	33.1	14.9	39.8	25.3	35.8	23.2	81.2	45.2
Mean		38.7	19.4	36.1	16.6	42.7	30.5	34.0	23.0	48.7	35.2
Tukey‡		11.7	9.4	9.6	5.3	15.4	11.7	9.3	8.0	31.5	26.5

† European *Miscanthus* Improvement project number.
‡ Tukey test applied to calculate the minimum significant difference between genotypes within a site and within a year at $P = 0.05$.

Table 6. Potassium concentration at autumn and winter harvests of 15 *Miscanthus* genotypes grown at five locations in Europe in the third growing season following planting. The four genotype groups were *M.* × *giganteus* (Gig), *M. sacchariflorus* (Sac), *M. sinensis* hybrids (Sin-H), and naturally occurring diploid *M. sinensis* (Sin).

Genotype group	EMI no.†	Sweden		Denmark		England		Germany		Portugal	
		Autumn	Winter	Autumn	Winter	Autumn	Winter	Autumn	Winter	Autumn	Winter
		K, $g\ kg^{-1}$ dry weight									
Gig	1					6.1	5.1	11.4	10.1	4.7	3.7
	2					7.7	6.2	12.4	10.1		
	3					10.0	8.8	9.6	10.8	7.0	4.4
	4					7.9	5.9	13.2	9.8	7.8	3.4
Sac	5			8.8	2.9	7.8	3.6	9.4	7.0	6.5	2.9
Sin-H	6	8.8	3.7	10.9	2.1	7.3	5.1	10.6	4.3	10.4	3.4
	7	11.2		11.2	4.5	12.1	8.2	12.2	6.4	7.7	4.3
	8	6.1	4.3	10.3	4.5	6.8	3.2	10.1	6.8	4.5	3.6
	9	9.8		15.8	2.6	10.7	10.5	11.6	6.1	8.5	2.5
	10	12.7	4.8	12.8	6.7	9.1	4.6	9.4	6.6	12.1	4.1
Sin	11	10.1	2.6	8.0	1.8	4.3	2.9	5.7	2.5	7.6	3.3
	12	10.5	2.5	8.1	1.3	4.6	1.8	5.6	2.6	8.3	2.6
	13	12.3	2.4	12.9	1.7	6.5	2.9	7.9	3.1	9.3	4.4
	14	6.6	1.7	9.2	1.2	3.9	2.2	6.0	2.9	5.7	2.8
	15	7.0	1.2	11.0	1.3	3.6	2.2	6.6	2.9	11.4	2.5
Mean		9.5	2.9	10.8	2.8	7.2	4.9	9.5	6.1	8.0	3.4
Tukey‡		5.9	3.4	5.2	2.0	3.6	4.1	4.0	4.6	7.9	5.2

† European *Miscanthus* Improvement project number.
‡ Tukey test applied to calculate the minimum significant difference between genotypes within a site and within a year at $P = 0.05$.

the shoots to the rhizomes also account for wintertime reductions in the N concentration of the delayed harvested biomass (Christian et al., 1997). Translocation effectiveness from the shoots to the rhizomes is certainly influenced by both genotype and local climatic interactions. Autumn frost kills shoots and may reduce or prevent effective N translocation. Consequently, late flowering and senescing genotypes such as *M.* × *giganteus* (no. 1–4), *M. sacchariflorus* (5), and some *M. sinensis* hybrids translocate less than early flowering and senescing *M. sinensis* genotypes (no. 11–15) in climates with autumn frosts. However, in Portugal where irrigation was used, new green shoots grew from the base of the *M. sinensis* plants after flowering in June so that mineral concentrations of harvested *M. sinensis* biomass were even higher than in the later-maturing genotypes.

The S concentration of plant material varied between 0.22 and 1.27 $g\ kg^{-1}$ dry matter, with significant differences between genotypes and countries (see mean squares in Table 3 for relative importance). Average autumn S concentrations were highest in Denmark (0.63 $g\ kg^{-1}$) and Portugal (0.75 $g\ kg^{-1}$), but these values did not differ significantly from the other countries (0.46–0.51 $g\ kg^{-1}$). In Denmark, the genotypes that contained the highest S concentrations were the *M. sinensis* hybrids, but in Germany, *M.* × *giganteus* and in Portugal, *M. sinensis* had the highest S values. Although a significant effect of the harvest time on S values was found in Germany and England, negligible reductions of S concentrations were recorded with the delayed harvest elsewhere.

Overall Performance of Genotypes

The most suitable genotypes for the production of solid biofuels should combine high yields and good com-

Table 7. Chloride concentration at autumn and winter harvests of 15 *Miscanthus* genotypes grown at five locations in Europe in the third growing season following planting. The four genotype groups were *M.* × *giganteus* (Gig), *M. sacchariflorus* (Sac), *M. sinensis* hybrids (Sin-H), and naturally occurring diploid *M. sinensis* (Sin).

Genotype group	EMI no.†	Sweden		Denmark		England		Germany		Portugal	
		Autumn	Winter	Autumn	Winter	Autumn	Winter	Autumn	Winter	Autumn	Winter
		Chloride, $g\ kg^{-1}$ dry weight									
Gig	1					5.2	3.0	1.7	1.0	3.7	3.2
	2					6.3	3.8	1.6	0.9		
	3					6.5	4.3	1.6	1.0	4.2	2.7
	4					6.5	3.7	1.8	0.9	4.3	2.6
Sac	5			5.9	1.5	6.0	2.3	1.6	0.8	4.8	2.6
Sin-H	6	4.9	1.7	5.5	0.8	5.0	2.6	1.6	0.6	5.2	1.8
	7	3.9		5.9	1.1	5.6	4.7	1.9	0.7	6.4	2.6
	8	2.9	1.6	4.0	1.5	3.9	1.4	1.3	0.7	2.5	1.3
	9	3.4		5.3	0.9	3.2	3.4	2.3	0.8	3.1	1.5
	10	5.4	2.8	4.6	1.7	4.6	1.6	1.3	0.9	4.6	1.0
Sin	11	5.9	0.9	4.4	0.6	3.0	1.0	1.5	0.4	4.5	1.7
	12	5.3	0.7	4.4	0.6	3.0	0.8	1.3	0.3	3.9	1.4
	13	6.1	0.8	6.6	0.6	4.5	1.6	1.5	0.3	6.6	2.0
	14	2.8	0.4	4.4	0.5	2.3	1.0	1.0	0.3	2.9	1.0
	15	3.5	0.5	5.1	0.5	3.3	1.4	0.8	0.2	9.8	1.1
Mean		4.4	1.2	5.1	0.9	4.6	2.4	1.5	0.7	4.8	1.9
Tukey‡		2.4	1.5	1.5	0.2	2.0	1.7	1.0	0.4	3.9	1.9

† European *Miscanthus* Improvement project number.
‡ Tukey test applied to calculate the minimum significant difference between genotypes within a site and within a year at $P = 0.05$.

Table 8. Nitrogen concentration at autumn and winter harvests of 15 *Miscanthus* genotypes grown at five locations in Europe in the third growing season following planting. The four genotype groups were *M.* × *giganteus* (Gig), *M. sacchariflorus* (Sac), *M. sinensis* hybrids (Sin-H), and naturally occurring diploid *M. sinensis* (Sin).

Genotype group	EMI no.†	Sweden		Denmark		England		Germany		Portugal	
		Autumn	Winter	Autumn	Winter	Autumn	Winter	Autumn	Winter	Autumn	Winter
		N, g kg^{-1} dry weight									
Gig	1					3.7	2.9	4.3	4.4	4.6	2.1
	2					3.4	2.4	4.4	4.3		
	3					3.9	3.0	4.1	4.1	4.7	2.0
	4					3.6	2.6	4.9	3.6	4.8	2.0
Sac	5			7.4	3.9	4.6	1.9	3.5	2.6	4.8	1.4
Sin-H	6	4.0	3.2	6.0	3.9	3.3	3.1	4.6	3.1	6.7	4.0
	7	5.7		6.6	5.8	4.8	4.2	5.9	4.9	4.9	2.2
	8	4.7	4.7	5.5	4.7	3.5	3.2	4.3	5.0	3.8	3.7
	9	5.3		9.4	6.8	6.1	4.4	6.7	5.0	5.8	3.7
	10	7.7	5.8	6.8	6.2	3.6	3.5	4.2	4.3	6.8	3.9
Sin	11	6.0	3.5	6.0	3.8	3.2	3.2	3.3	2.4	7.0	5.6
	12	5.2	3.4	6.5	3.6	3.1	2.9	4.3	2.5	7.0	4.7
	13	4.5	3.1	5.7	3.7	3.7	2.6	4.6	2.7	6.0	5.0
	14	3.3	4.1	5.6	4.0	3.1	3.2	3.1	2.4	6.3	4.4
	15	3.5	3.5	4.9	4.0	3.0	2.7	3.4	3.2	7.5	5.2
Mean		5.0	3.9	6.4	4.6	3.8	3.1	4.4	3.6	5.7	3.6
Tukey‡		2.2	2.9	1.5	1.6	1.9	1.9	1.9	2.3	2.6	2.8

† European *Miscanthus* Improvement project number.
‡ Tukey test applied to calculate the minimum significant difference between genotypes within a site and within a year at $P = 0.05$.

bustion qualities. The data presented here show that delayed harvest led to significant improvements in combustion quality for all genotypes. Because harvesting and drying costs decrease with falling moisture contents, winter or early-spring harvests are probably more economical than autumn harvests (van den Heuvel, 1995; Huisman et al., 1997).

The highest biomass yields in winter were recorded for *M. sinensis* hybrid no. 10 in both Sweden and Denmark (Table 3). However, the concentrations of ash, K, Cl, N, and S of genotype no. 10 were relatively high in both Denmark and Sweden. High-yielding genotypes are often characterized by the maintenance of green leaf late into the growing season and late flowering. While these characteristics lengthen the effective growing season, they have the disadvantage of maintaining higher mineral and water contents than the earlier-senescing genotypes at harvest. Therefore, as with many crops, there is an antagonism between yield and quality, and the best choice of genotypes may depend on the demands of the biomass user.

To date, biomass fuel standards only exist for certain fuels in a small number of European countries (IER, 2002). Standards are available for wood chips in Austria, firewood and agricultural residues and by products in Italy, and wood pellets and briquettes in Germany and Sweden. In 1997, a European Union standardization initiative began developing biomass fuel standards, and it is expected that these will be published during 2003. However, these fuel standards will have to be adjusted for (i) the combustion technique (e.g., type of combustion unit and size), (ii) the type of fuel (e.g., wood or stalky biomass), and (iii) the fuel format (e.g., pellets or chips). Targets discussed for biomass fuels are moisture concentrations from 200 to 300 g H_2O kg^{-1} fresh matter, N concentrations below 10 to 20 g kg^{-1}, and Cl concentrations <3 g kg^{-1} (IER, 2002). We have shown here that these levels are generally attainable with *Miscanthus* spp. grown throughout much of Europe. It should be noted that lower thresholds (6 g N kg^{-1} dry matter and 1 g Cl kg^{-1} dry matter) have been discussed for wood biomass (Obernberger, 1998), but these are too demanding for stalky biomass such as *Miscanthus* spp. and straw.

For the Swedish and Danish sites *M. sinensis* hybrid no. 6 offers a good compromise between optimizing yield and quality because, compared with other *M. sinensis* hybrids, it is characterized by low moisture, ash, K, Cl, N, and S concentrations at harvest. At the German and English sites *M.* × *giganteus* performed best in terms of yield, and apart from high K concentrations, its quality is as good as, or better than, the *M. sinensis* hybrids. In England, the *M. sinensis* hybrids no. 6, 7, and 9 outyielded *M.* × *giganteus*. However, their ash and N concentrations were higher than those of *M.* × *giganteus* so that no advantage of these new hybrids over *M.* × *giganteus* was apparent. In Portugal, the *stay-green* genotype no. 7 outyielded all other *Miscanthus* genotypes, but due to late senescence, the moisture, K, and ash concentrations of this genotype were significantly higher than for *M.* × *giganteus*.

CONCLUSIONS

We have shown for *Miscanthus* genotypes grown across Europe from Sweden to Portugal that local environmental conditions at a site had strong effects on yield and chemical composition. Delayed harvesting time proved an effective strategy for improving the quality of the biomass of all *Miscanthus* genotypes. The processes that influence the genotypic differences in quality at delayed harvest were time of senescence of shoots, rate of translocation of minerals to the rhizome, leaf detachment, and leaching.

As expected, the highest-yielding genotypes at a particular site did not produce the highest quality biomass. For southern European sites, late flowering and senescing genotypes, such as *M.* × *giganteus* and selected *M.*

sinensis hybrids, had higher yield potentials due to a longer growing season than early flowering and senescing genotypes, such as nonhybrid *M. sinensis* genotypes. At more northerly sites, where nonhybrid *M. sinensis* flowered later, yields from these genotypes become more competitive. Selected hybrid *M. sinensis* combined (i) the overwintering capacity essential for reliable stand survival with (ii) an optimal length of the growing season for high yields and (iii) high combustion qualities. For midlatitudes in Europe where winters are mild, *M.* × *giganteus* is probably the preferred genotype.

As the setting of quality standards for biomass may be expected in future to reduce gaseous emissions and to avoid technical problems in the combustion units, it is likely that these standards will become the main determinant for selection of genotypes. However, as the newly bred *M. sinensis* hybrids showed considerable quality variation from site to site, it can be anticipated that genotypes suitable for most ecological regions of Europe can be selected following further breeding.

ACKNOWLEDGMENTS

This work was funded by the EC contract no. FAIR3 CT-96–1392. Thanks to the Ihinger Hof field station, Sabine Schneider, and Birgit Beierl for technical assistance; Dr. Jörn Breuer from Landesanstalt für Chemie, Hohenheim for laboratory analyses; Jens Bonderup Kjeldsen and Kaj Eskesen for their assistance in the Danish field experiment; and Nicola Yates in Rothamsted.

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