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Field Crops Research 63 (1999) 3–11

Field Crops Research

Effect of irrigation and nitrogen fertilization on biomass yield and efficiency of energy use in crop production of *Miscanthus*

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Received 11 August 1998; accepted 20 March 1999

Abstract

The perennial C_4 grass *Miscanthus* has been proposed as a biomass energy crop in Europe. Effects of crop age, irrigation and nitrogen fertilization on biomass and energy yields and N content of *Miscanthus* were investigated and the energy costs of production determined. After an establishment period of 1 year, cultivation of *Miscanthus* resulted in a dry matter production of over 37 t ha^{-1} year^{-1} over a period of 4 years. Irrigation and nitrogen level greatly affected *Miscanthus* biomass yield. In absence of N fertilization, irrigation did not modify biomass yield and the effect of irrigation increased with the increase in N level. The average N response ranged from 37 to 50 kg biomass kg^{-1} N applied. Because the calorific value of *Miscanthus* biomass (16.5 MJ kg^{-1}) was not affected by irrigation and N fertilization, energy production depended exclusively on biomass yield. Maximum energy yield was 564 GJ ha^{-1} year^{-1}. Without N supply and irrigation, energy yield was 291 GJ h^{-1}. Net energy yield, calculated as the difference between energy output and input, but without inclusion of drying costs, was 543 GJ ha^{-1} with N fertilization and irrigation and 284 GJ ha^{-1} without; the ratios of energy output to input in crop production were 22 and 47, respectively.

Keywords: Crop age; Energetic efficiency; Fertilization; Irrigation; *Miscanthus*; Nitrogen

1. Introduction

Several plant species have been investigated for their potential as biomass crops. As biomass conversion techniques have been advanced, interest has focused on the cultivation of *Miscanthus* species, which have potential for high yields of biomass in European conditions with yields of 25 to 35 t ha^{-1} year^{-1} once the crop has been established (Schwarz, 1993; van der Werf et al., 1993; Hotz, 1996; Himken et al., 1997; Venendaal et al., 1997).

Miscanthus is a C_4 rhizomatous perennial grass originating from Asia. In temperate climates, its growth is limited by low temperature. In Europe it begins growth in April and continues until halted by frost in November. In winter the above-ground parts are killed by frost. Regrowth occurs from crowns in spring. Nutrients and carbohydrates stored in rhizomes during fall are mobilized to shoots in late April/early May, supporting rapid growth. The plant has an extensive root system that responds quickly to a rapid demand for nutrients during spring growth, thus

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PII: S0378-4290(99)00022-2

reducing the risk of nitrate leaching (Himken et al., 1997).

Nursery plants are planted in spring and the crop can be harvested annually for up to 15 years after establishment (Schwarz et al., 1994). Although maximum above-ground dry matter yield is attained in late summer, harvest can be delayed until February/March when the crop has its highest dry matter concentration (Petrini et al., 1996; Himken et al., 1997). This is important for net energy production, as energy requirements for drying of the plant material prior to combustion is less for standing dead material than for green material. At harvest, shoots are mechanically cut near ground level.

The C_4 photosynthetic pathway contributes to high water-use efficiency and to a low nitrogen content of the biomass. Long (1983) and Beale and Long (1997) calculated a requirement of 450 mm water and 92 kg N ha^{-1} for a crop producing an above-ground harvest of 15 t ha^{-1} dry matter. It has been reported that the effect of N fertilization on biomass yield is not high: Schwarz et al. (1994), reported an increase of only 1.1 t ha^{-1} in biomass dry weight (from 20.6 to 21.7 t ha^{-1}) with an increase in N level from 0 to 180 kg ha^{-1} in a 3-year-old crop. Himken et al. (1997) calculated an annual removal of N from the field (equivalent to the fertilizer demand of an established *Miscanthus* crop) around 50 to 70 kg N ha^{-1} in a 4-year-old crop. Christian et al. (1997) found, in 1-year-old plants, that of the 117 kg ha^{-1} N taken up by the crop, only 23 kg ha^{-1} (38%) was derived from the fertilizer.

Long-term experience on *Miscanthus* is still lacking, especially about how to establish a good crop, about its nutritional demands and how yield will vary in the course of an estimated 10–20 years of usage.

The objective of this research was to determine the effects of irrigation and nitrogen fertilizer on yield and nitrogen content of *Miscanthus sinensis* cv. Giganteus. In addition, the use of energy resources was analyzed to determine the energy cost of management techniques and the energy balance of the crop.

2. Materials and methods

2.1. Crop culture

A field study was conducted at Pisa (43°40′N, 10°19′E) in Italy from 1992 to 1995. Soil physical and chemical properties were 34% sand, 21% silt, 45% clay, pH 7.2, 2.15% organic matter (Walkley-Black method), 0.12% nitrogen (Kjeldahl method), 33 $\mu g\ g^{-1}$ available P (Olsen method), and 22 $\mu g\ g^{-1}$ available K (Dirks Scheffer method). During the trial period, no water table was observed within the top 1.2 m of soil.

Age of crop at harvest was 1, 2, 3 or 4 years. Treatments were crop age, irrigation, and nitrogen rate. Irrigation treatments were unirrigated and replacement of 100% estimated evapotranspiration. Nitrogen treatments were 0, 100 and 200 kg ha^{-1} of N. These were applied in the establishment year (1992), as 50% preplant and 50% sidedressing when *Miscanthus* plants were 0.35–0.45 m tall. In the following years, N fertilizer was applied entirely at the start of growth in spring (approximately on 15 April). Nitrogen was applied as urea.

The experimental design was a split plot with year as main plots, irrigation treatments as sub-plots and nitrogen rates as sub-sub-plots. Plots were replicated three times and measured 6 m long and 5 m wide, separated by a minimum of 3 m. *Miscanthus* cv. Giganteus was used. Planting was carried out on 16 April 1992 using potted plants produced by micropropagation. At that time, the plants were about 0.20 m tall. *Miscanthus* was grown in 0.50 m wide rows at a population of 400 00 plants ha^{-1}. The previous crop was barley. Tillage was conducted in the autumn of 1991 and consisted of medium-depth ploughing (30–40 cm). Seedbed preparation was conducted in spring, immediately before planting, by a pass with a double-disking harrow and a pass with a field cultivator. Preplant fertilizer was distributed at a rate of 87 kg P ha^{-1} (triple superphosphate) and 83 kg K ha^{-1} (potassium sulphate). Plots were kept weed-free by handweeding. Water was distributed by drip irrigation. After sidedressing, irrigation lines were permanently installed in the centre of the interrow. Flow application rate was 4L h^{-1} m^{-1} of tubing (1 dripper per metre). The soil profile was presumed to be at field capacity at planting. Irrigation treatment was designed so that rainfall plus irrigation replaced a portion of the soil moisture lost to estimated evapotranspiration. The amount of water given daily was based upon the potential evapotranspiration data (E_0) of the previous day, estimated from Class A pan evaporation. Actual evapotranspiration was calculated as $E = k_c E_0$ where k_c is the crop coefficient. Because

Table 1
Seasonal irrigation and precipitation during the four research years

Year	Water treatment	Seasonal irrigation (mm)	Precipitation[a] (mm)	Total (mm)
1992	Rainfed	–	399	399
	Irrigated	224	399	623
1993	Rainfed	–	131	131
	Irrigated	228	131	359
1994	Rainfed	–	201	201
	Irrigated	250	201	451
1995	Rainfed	–	186	186
	Irrigated	219	186	405

[a] Total precipitation from planting or start of growth until harvest. The 110-year-average precipitation from 15 April to 30 September equals 330 mm.

Miscanthus k_c is not known, we used a value for sorghum as reported by Tarantino and Onofri (1988), which increases from 0.33 at 20 days after emergence to 1.23 at anthesis and declines to 0.76 at maturity. Irrigation, rainfall before and after the beginning of irrigation, and total water supply are presented in Table 1. Irrigation periods were 24 July–8 August 1992, 28 July–16 August 1993, 30 June–22 August 1994 and 27 June–9 August 1995. No pest infestation was detected during the experimental period.

Harvesting was carried out at anthesis, when maximum biomass yield occurred according to Petrini et al. (1996). Harvest dates were 14 October in 1992, 5 October in 1993, 8 October in 1994 and 10 October in 1995. Plants in a 1 m^2 area were harvested by cutting at ground level, separated into stems (including leaf sheaths and inflorescences) and leaf lamina, and weighed to determine fresh weight. In all figures and tables, these fractions are referred to as stems and leaves. The subsamples were placed in a forced-draft oven at 75°C for 72 h and were ground after determination of dry weight. Nitrogen concentration was determined by the micro-Kjeldahl method. A homogeneous dried sample of the entire aerial plant part was ground to pass through No. 4 sieve (4.75 mm), and burnt in an oxygen bomb calorimeter (Gallenkamp autobomb, Leicester, UK) to determine calorific value. The energy yield of *Miscanthus* biomass was calculated by multiplying the calorific value per unit of biomass by the above-ground dry matter yield.

2.2. Energy analysis

Energy analysis of *Miscanthus* biomass production was carried out by determining energy costs for fabrication and repairs of machinery, for fertilizer and planting material and for fuel consumption for the various operations. Energy costs for delivering the production outside the field and for storage were not calculated. In our research, *Miscanthus* was propagated with in vitro micropropagated plants, but, hypothesising establishment in an extensive cultivation system, the best method of propagation is by rhizome cuttings. Therefore, that method is considered in the determination of crop energy cost following the approach suggested by Heichel (1980). Because the harvested plant material was anatomically similar to the organs or tissues used for establishing the crop, the quantity of material used for propagation was subtracted from the total yield of the crop, with the output energy of the cropping system being the 'net above seed requirements'. In our analysis, the energy cost of propagation material was considered negligible, since the biomass involved was less than 3% of the total yield of the crop.

Energy inputs for machinery were determined, following Doering (1980), by estimating energy consumption for the fabrication and the repairing of the machinery utilized for *Miscanthus* cultivation, and by calculating the annual per hectare machinery cost. We assumed that machinery and implements were used on 200 ha, and machine life was 10 years. In Table 2, the machinery used in *Miscanthus* cultivation and the weight of each piece of machinery are reported. The energy cost for fertilizer manufacturing was 59.9 MJ kg^{-1} for N, 5.5 MJ kg^{-1} for P and 5.6 MJ kg^{-1} for K (Lockeretz, 1980). Fuel costs of various management operations were calculated (Table 3) by determining diesel consumption and by multiplying those values by the heat of combustion of

Table 2
Weight of machinery utilized for *Miscanthus* cultivation, annual per hectare machinery weight and energy consumption for the fabrication and repair parts and materials of the machinery. We assumed that machinery and implements were used on 200 ha, and machine life was 10 years. Tractors utilized were 204 kW for plowing, 74 kW for disk harrowing, 59 kW for rotary harrowing, and 37 kW for fertilization and harrowing

Operation	Weight (kg)		Energy cost[a]	
	Tractor	Implement	Tractor + Implement kg ha^{-1} year^{-1}	MJ ha^{-1} year^{-1}
Plowing	6680	1350	4.0	301
Disk harrowing	4980	1510	3.2	241
Rotary harrowing	3960	650	2.3	173
Fertilization 50% N–P–K	1980	160	1.1	83
Fertilization 50% N	1980	160	1.1	83
Planting	2300	–	1.2	90
Harvesting	1980	5800	3.9	294

[a] The energy coefficient used in 75.36 MJ kg^{-1}.

diesel fuel (45.8 MJ kg^{-1}). While we used microirrigation in the experiment in order to have accurate water management, crop energy cost was based on the sprinkler irrigation method. The energy cost for irrigation was determined by the formula reported by Batty and Keller (1980) and adapted from Knutson et al. (1977): energy cost (MJ) = 550 × L × A, where L is the lift in meters and A is the amount of water pumped in m ha^{-1}. It was assumed that water was lifted 10 m and delivered to the field with a 20% loss in conveyance and application.

All variables were analyzed with standard split-plot analysis of variance techniques to test effects of year, irrigation, nitrogen supply, and their interactions. Significantly different means were separated at 0.05 probability level by the least significant difference test (Snedecor and Cochran, 1980).

3. Results

Precipitation during the 1992 growing season was 69 mm greater than the 110-year-average (330 mm), while those in 1993, 1994 and 1995 were lower by 199, 129 and 144 mm respectively (Table 1). The amounts of water distributed by irrigation were about the same in all years, ranging from 219 to 250 mm.

3.1. Dry weight

Dry weight of *Miscanthus* biomass, stems and leaves were affected by year of harvest, irrigation and nitrogen level mean effects, and by irrigation × nitrogen level interaction, while it was not affected by the other interactions. Averaged over

Table 3
Annual fuel energetic cost for machine operations involved in *Miscanthus* production

N level (kg ha^{-1})	Plowing (MJ ha^{-1})	Harrowing (MJ ha^{-1})		Fertilization (MJ ha^{-1})		Planting (MJ ha^{-1})	Harvesting (MJ ha^{-1})	Total (MJ ha^{-1})
		Disk	Rotary	P–K	N			
Establishment year								
0	1924	651	504	111		837	3770	7797
100	1924	651	504	111	90	837	3770	7887
200	1924	651	504	111	137	837	3770	7934
Following years[a]								
0	–	–	–	–		–	3770	3770
100	–	–	–	–	90	–	3770	3860
200	–	–	–	–	137	–	3770	3907

[a] Mean values of year 2, 3 and 4.

Table 4
Dry weight and nitrogen content of leaves, stems and total biomass of *Miscanthus* observed over four production years. Values are averaged over three N rates and irrigated/rainfed conditions

Year of harvest	Leaves	Stems	Biomass
Dry weight (t ha^{-1})			
1	5.0 a	10 a	15 a
2	5.6 ab	20 b	26 b
3	6.6 b	20 b	27 b
4	6.7 b	19 b	26 b
N content (kg ha^{-1})			
1	95 a	47 a	143 a
2	75 b	82 c	158 a
3	77 b	77 bc	144 a
4	74 b	70 b	143 a

Values within the same column followed by the same letter are not significantly different at the 0.05 probability level.

irrigation and nitrogen levels, dry weight of biomass, stems and leaves increased from the establishment year to the following one and did not vary thereafter (Table 4).

Nitrogen level and irrigation increased dry weight of biomass. The effect of irrigation depended on nitrogen level: in absence of nitrogen fertilization, dry weight of biomass was not affected by irrigation and increased with N level in both rainfed and irrigated crops. The increase was greater in irrigated crops than in the rainfed crops, thus with 100 kg N ha^{-1} irrigation increased dry weight of biomass by 3.7 t ha^{-1} and with 200 kg N ha^{-1} irrigation increased dry weight of biomass by 9.8 t ha^{-1} (Fig. 1). Maximum biomass of *Miscanthus* crop was 37.5 t ha^{-1}, and was attained in the 3-year-old crop with 200 kg N ha^{-1} and irrigation.

The partitioning of biomass between leaves and stems varied over years and was not affected either by irrigation or nitrogen level. From the establishment year to the following ones, the proportion of leaves decreased and that of stems increased, and no significant difference was detected among the older crops (Fig. 2).

Water content of *Miscanthus* biomass, which is important because it affects both transport and storage, was not affected by year, irrigation or nitrogen level. Averaged over all treatments, water content of leaves was about 65% and that of stems about 47%.

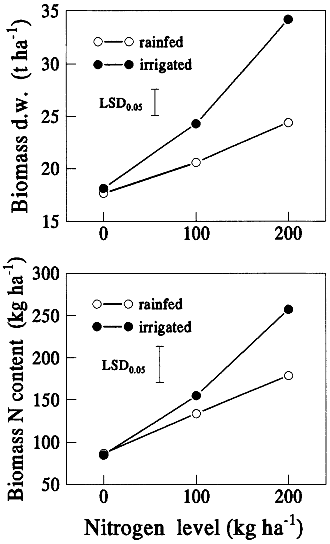

Fig. 1. Dry weight (top) and nitrogen content (bottom) of rainfed and irrigated *Miscanthus* crops in response to nitrogen fertilization. Values are averaged over 4 years.

3.2. Nitrogen concentration and content

Nitrogen concentrations of biomass, leaves, and stems were affected only by N fertilization. When N level increased from 0 to 200 kg ha^{-1}, N concen-

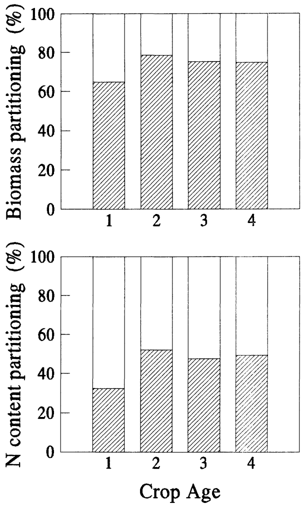

Fig. 2. Partitioning of *Miscanthus* dry weight (top) and nitrogen content (bottom) between leaves (empty area) and stems (filled area) observed over four production years. Values are averaged over three N rates and irrigated/rainfed conditions.

Table 5
Nitrogen concentration of leaves, stems and total biomass of *Miscanthus* in response to three nitrogen levels. Values are averaged over 4 years and irrigated/rainfed conditions

Nitrogen level (kg ha^{-1})	Leaves (g kg^{-1})	Stems (g kg^{-1})	Biomass (g kg^{-1})
0	10.9 a	2.8 a	4.8 a
100	13.7 b	3.9 b	6.4 b
200	14.8 c	4.8 c	7.5 c

Values within the same column followed by the same letter are not significantly different at the 0.05 probability level.

tration, averaged over years and irrigation level, increased from 4.8 to 7.5 g kg $^{-1}$ in biomass (Table 5).

Nitrogen content of biomass, stems and leaves was affected by irrigation × nitrogen interaction and N content of stems and leaves was also affected by crop age mean effect. Nitrogen content of leaves was 95 kg ha^{-1} in the establishment year and decreased to 74 kg ha^{-1} in the following years (Table 4). By contrast, nitrogen content of stems increased from 47 kg ha^{-1} in the establishment year to about 75 kg ha^{-1} in the following ones. As a consequence, N content of biomass was not significantly affected over years. The partitioning of N content between leaves and stems was affected only by year of harvest (Fig. 2). Over years, the quantity of N in leaves decreased and that in stems increased, but no significant differences were detected after year 1.

Similar to dry weight, N content of biomass was not affected by irrigation in absence of nitrogen fertilization, while N fertilizer increased N content of biomass with a greater effect when the crop was irrigated. Averaged over years, N content of biomass of the rainfed crop was increased by the highest N level by 92 kg ha^{-1}, and that of the irrigated crop by 171 kg ha^{-1} (Fig. 1). The effects on N content of stems and leaves was similar to that on biomass. The maximum N content of *Miscanthus* crop was 290 kg ha^{-1}, attained in the 3-year-old crop with 200 kg N ha^{-1} and irrigation.

3.3. Energy balance

The total energy input of *Miscanthus* production ranged from 13 to 27 GJ ha^{-1} in the establishing year and from 4 to 18 GJ ha^{-1} in the following years, depending on the irrigation or nitrogen fertilization (Table 6). The sum of machinery and fuel inputs represents the cost of all management techniques applied to the crop. After the establishment year, it amounted to 100% of the total energy needed for crop production in absence of irrigation and N fertilization, and to 25% with both irrigation and highest N level. The use of N fertilizer involved energy costs, each year, of 6 GJ ha^{-1} with 100 kg N ha^{-1} and of 12 GJ ha^{-1} with 200 kg N ha^{-1}. These values represent 32% and 48% of total energy inputs in the establishing year and 58% and 73% in the following years, respectively. Irrigation required less energy: only 1.5 GJ ha^{-1}, representing 6–10% of total energy inputs in the establishing year and 6–27% in the following ones.

The average calorific value of dry *Miscanthus* biomass (16.5 MJ kg^{-1}) was not affected by nitrogen supply or irrigation in any year of the trial. Therefore, the effects of treatments on energy yield of the crop were equal to those on biomass yield. Maximum energy yield of *Miscanthus* was 564 GJ ha^{-1}, obtained with 200 kg N ha^{-1} and irrigation. On the contrary, without N supply and irrigation, energy yield was 291 GJ ha^{-1}.

To evaluate the performance of the *Miscanthus* bioenergy system, we considered net energy yield, calculated as the difference between energy output and energy input per hectare, and efficiency of energy production, calculated as the ratio between energy output and energy input per hectare. Both net energy yield and efficiency of energy production were affected by irrigation and N level. Without N fertilization, net energy yield was not affected by irrigation, whereas it increased with the increase of N level in both rainfed and irrigated crops. The increase was greater in the irrigated crop than in the rainfed one, in fact with 100 kg N ha^{-1}, irrigation increased net energy yield by 60 GJ ha^{-1} and, with 200 kg N ha^{-1}, irrigation increased net energy yield by 160 GJ ha^{-1} (Fig. 3). Maximum net energy yield, of about 600 GJ ha^{-1}, was recorded in the 3-year-old crop irrigated and fertilized with the highest N level.

The efficiency of energy production decreased with the increase in N fertilization but the effect was different whether the crop was rainfed or irrigated (Fig. 3). Averaged over years, energy efficiency was greater in the rainfed crop than in the irrigated one in absence of N fertilizer, whereas with 100 kg N ha^{-1}

Table 6
Annual energy inputs for *Miscanthus* cultivation in the establishment year and in the following years in response to irrigation and to three nitrogen levels

Irrigation	N level (kg ha^{-1})	Machinery (MJ ha^{-1})	Fuel (MJ ha^{-1})	Phosphorus (MJ ha^{-1})	Potassium (MJ ha^{-1})	Nitrogen (MJ ha^{-1})	Irrigation (MJ ha^{-1})	Total (MJ ha^{-1})
Establishment year								
Rainfed	0	1182	7797	2512	1340			12 831
	100	1265	7887	2512	1340	5 987		18 991
	200	1265	7934	2512	1340	11 970		25 021
Irrigated	0	1182	7797	2512	1340		1479	14 310
	100	1265	7887	2512	1340	5 987	1479	20 470
	200	1265	7934	2512	1340	11 970	1479	26 500
Following years[a]								
Rainfed	0	294	3770	–	–			4 064
	100	377	3907	–	–	5 987		10 271
	200	377	3979	–	–	11 970		16 326
Irrigated	0	294	3770	–	–		1534	5 598
	100	377	3907	–	–	5 987	1534	11 805
	200	377	3979	–	–	11 970	1534	17 860

[a] Mean values of years 2, 3 and 4.

no difference was found owing to irrigation, and with 200 kg N ha^{-1} the efficiency was greater in the irrigated crop. Thus, when nitrogen was not applied, it was better not to irrigate, while with a high N level it was better to irrigate, since irrigation improved energy efficiency. Maximum energy efficiency of over 80 J J^{-1} was recorded in the rainfed 2-, 3-, and 4-year-old crops without N fertilization.

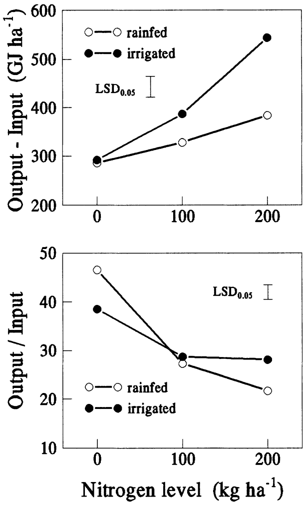

Fig. 3. Net energy yield (top) and efficiency of energy production (bottom) of *Miscanthus* cultivation in response to nitrogen fertilization. Values are averaged over 4 years.

If the analysis is carried out supposing a crop cycle length of 15 years, the costs of crop establishment will be distributed in a longer period and their incidence will decrease; likewise, the lower yield in the establishment year is distributed in a longer period and its influence decreases. Consequently, an annual maximum net energy yield of about 600 GJ ha^{-1} and an annual maximum energy efficiency of over 150 J J^{-1} are expected, with irrigation and the highest N level and without irrigation and N fertilization, respectively.

4. Conclusions

After an establishing period of about 1 year, the cultivation of *Mscanthus* resulted in a dry matter production of over 37 t ha^{-1} year^{-1} during the next 4 years when the crop was well irrigated and fertilized. In the absence of N fertilization, irrigation did not modify biomass yield, the effect of irrigation increased with the increase in N level. The effect can be estimated as +3.7 t ha^{-1} with 100 kg N ha^{-1}

and +9.8 t ha^{-1} with 200 kg N ha^{-1}. Increase in nitrogen level also increased N concentration of biomass, from 4.8 g kg^{-1} at the zero N level to 7.5 g kg^{-1} at the 200 kg N level. However, even the highest N concentration is less than the critical limit of 10 g kg^{-1} N for minimum N oxides emissions during combustion of biomass fuels (Lewandowski and Kicherer, 1997).

Water content of *Miscanthus* biomass was about 53% in autumn, considerably higher than the maximum limit of 23% required to ensure good storability of biomass (Lewandowski and Kicherer, 1997). A consequence of the high water content is that the harvested plant material must be dried. The water content of *Miscanthus* at harvest depends on the harvesting season. In most countries, *Miscanthus* is harvested in spring when the dead, overwintered vegetative matter is at its driest (15–25%) and can be stored with less risk of fungal attack. On the other hand, autumn harvest of *Miscanthus* has environmental benefits, such as less soil compaction, since the soil is wet at the end of winter and use of heavy machinery may damage the soil.

The calorific value of *Miscanthus* biomass was about 16.5 MJ kg^{-1} and was not affected by irrigation and N fertilization. Therefore, energy production depended exclusively on biomass yield. Maximum energy yield was 564 GJ ha^{-1}, obtained after the establishing year with 200 kg N ha^{-1} and irrigation. On the contrary, without N supply and irrigation, energy yield was 291 GJ ha^{-1}. Net energy yield, calculated as the difference between energy output and energy input per hectare, was 543 GJ ha^{-1} in the former case the 284 GJ ha^{-1} in the latter, assuming an energetic input of 20.6 and 6.5 GJ ha^{-1} respectively, averaged over years of cultivation. The ratio of energy output to energy input in crop production was 22–47, the range depending on whether irrigation or N fertilization were applied or not. These values are very much higher than those determined on *Miscanthus* by Lewandowski et al. (1995). The difference probably depends on the fact that in our research *Miscanthus* was harvested when greatest biomass was attained. At this stage, the water content was at its highest value, but the energy requirements for drying of the plant material prior to combustion were not included in our analysis.

Acknowledgements

This research was supported by the Italian Ministry of Food Agriculture and Forestry Resources, Project PRisCa. The work is to be attributed to all four authors in equal parts.

References

Batty, J.C., Keller, J., 1980. Energy requirements for irrigation. In: Pimentel, D. (Ed.), Handbook of Energy Utilization in Agriculture. CRC Press, Boca Raton, Florida, pp. 35–54.

Beale, C.V., Long, S.P., 1997. Seasonal dynamics of nutrient accumulation and partitioning in the perennial C4-grass *Miscanthus* × *giganteus* and *Spartina cynosuroides*. Biomass Bioenergy 12, 419–428.

Christian, D.G., Poulton, P.R., Riche, A.B., Yates, N.E., 1997. The recovery of 15N-labelled fertilizer applied to *Miscanthus* × *giganteus*. Biomass Bioenergy 12, 21–24.

Doering, O.C. III, 1980. Accounting for energy in farm machinery and buildings. In: Pimentel, D. (Ed.), Handbook of Energy Utilization in Agriculture. CRC Press, Boca Raton, Florida, pp. 9–24.

Heichel, G.H., 1980. Assessing the fossil energy costs of propagating agricultural crops. In: Pimentel, D. (Ed.), Handbook of Energy Utilization in Agriculture. CRC Press, Boca Raton, Florida, pp. 27–33.

Himken, N., Lammel, J., Neukirchen, D., Czypionka-Krause, U., Olfs, H.-W., 1997. Cultivation of *Miscanthus* under West European conditions: Seasonal changes in dry matter production, nutrient uptake and remobilization. Plant Soil 189, 117–126.

Hotz, A., 1996. Screening of different *Miscanthus* cultivars in respect of their productivity and usability as a raw material for energy and industry. In: Chartier, P., Ferrero, G.L., Henius, U.M., Wiinblad, M. (Eds.), 9th European Bioenergy Conf. Proc., 24–27 June 1996, Copenhagen, Denmark. Elsevier Science, Oxford, UK, 2294 pp.

Knutson, G.D., Curley, R.G., Roberts, E.B., Hagan, R.M., Cervinka, V., 1977. Pumping energy requirements for irrigation in California. Special Publication 3215. Division of Agricultural Science, University of California, Oakland.

Lewandowski, I., Kicherer, A., 1997. Combustion quality of biomass: practical relevance and experiments to modify the biomass quality of *Mascanthus* × *giganteus*. Eur. J. Agron. 6, 163–177.

Lewandowski, I., Kicherer, A., Vonier, P., 1995. CO_2-balance for the cultivation and combustion of *Miscanthus*. Biomass Bioenergy 8, 81–90.

Lockeretz, W., 1980. Energy inputs for nitrogen, phosphorus, and potash fertilizers. In: Pimentel, D. (Ed.), Handbook of Energy Utilization in Agriculture. CRC Press, Boca Raton, Florida, pp. 23–26.

Long, S.P., 1983. C4 photosynthesis at low temperatures. Plant Cell Environ. 6, 345–363.

Petrini, C., Bazzocchi, R., Bonari, E., Ercoli, L., Masoni, A., 1996. Effect of irrigation and nitrogen supply on biomass production from *Miscanthus* in Northern-Central Italy. Agric. Med. 126, 275–284.

Schwarz, H., 1993. *Miscanthus sinensis* 'Giganteus' production on several sites in Austria. Biomass Bioenergy 5, 413–419.

Schwarz, H., Liebhard, P., Ehrendorfer, K., Ruckenmauer, P., 1994. The effect of fertilization on yield and quality of *Miscanthus sinensis* 'Giganteus'. Industrial Crops Products 2, 153–159.

Snedecor, G.W., Cochran, W.G., 1980. Statistical Methods, 7th ed. Iowa State University Press, Ames.

Tarantino, E., Onofri, M., 1988. Determinazione dei coefficienti colturali mediante lisimetri. Symposium Irrigazione e Ricerca Proc., Bologna, Italy, 1988. Cartotecniche Meridionali, Foggia, pp. 119–136.

van der Werf, H.M.G., Meijer, W.J.M., Mathijssen, E.W.J.M., Darwinkel, A., 1993. Potential dry matter production of *Miscanthus sinensis* in the Netherlands. Industrial Crops Products 1, 203–210.

Venendaal, R., Jorgensen, U., Foster, C.A., 1997. European energy crops: a synthesis. Biomass Bioenergy 13, 147–185.