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Growth, yield and mineral content of *Miscanthus* × *giganteus* grown as a biofuel for 14 successive harvests

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ABSTRACT

Miscanthus × *giganteus*, a perennial rhizomatous grass commercially used as a biofuel crop was grown in a field experiment on a silty clay loam soil for 14 years. There were 3 rates of fertilizer nitrogen (N), none (control), 60 kg N ha^{-1} yr^{-1} and 120 kg N ha^{-1} yr^{-1} as cumulative applications. The crop was harvested in winter and dry matter yield measured. N did not influence yield. Yield, which increased for the first 6 years, decreased in years 7 and 8, but then increased again and was highest in the 10th year averaging 17.7 t ha^{-1} across all treatments. Differences in total production over the14 years were only 5% between the highest and lowest yielding treatments and averaged 178.9 t ha^{-1} equivalent to 12.8 t ha^{-1} yr^{-1}. In the first 10 harvests, 92% of dry matter was stem. Although the study showed N fertilizer was not required, it is considered that an application of 7 kg P ha^{-1} yr^{-1} and 100 kg K ha^{-1} yr^{-1} would avoid soil reserve depletion. Pesticides were not required every year and the crop can be considered as low input with a high level of sustainability for at least 14 years.

1. Introduction

Recent EU and UK governmental reports predict a more prominent future for biomass crops as a renewable fuel for heat, electrical and motive power production (Anon., 2003; CEC, 2000; European Commission, 1996). The main policy driver is the consequent net reduction of atmospheric emissions of carbon dioxide (CO_2), a greenhouse gas emitted mainly by burning fossil fuels. Plant biomass is often termed a CO_2-neutral fuel, releasing on conversion only CO_2 previously removed from the atmosphere during photosynthesis. However this is not strictly true as some fossil derived CO_2 evolves as a result of its cultivation, planting and harvesting and the manufacture of any agrochemicals used. However, for electrical generation, using plant biomass results in a large decrease in net fossil CO_2 emission when substituted for a fossil fuel (DTI, 1999).

Nonhebel (2002) considered that for a plant species to have potential as an energy crop, the bioenergy yield must be produced with a low level of inputs that themselves require minimal energy for their production and use so that a positive energy balance is achieved. One species with potential as an energy crop is *Miscanthus* × *giganteus* (subsequently referred to as *Miscanthus*) which is a tall growing C-4 perennial rhizomatous grass from Asia (Greef and Deuter, 1993). There is an estimated 10,000 ha of *Miscanthus* in the UK (Nix, 2007). The majority of the crop is being used for heat generation in power stations. The energy output of *Miscanthus* in comparison with energy input has been reported to be circa 15–20:1 (Lewandowski and Kicherer, 1997). In recent years there have been several studies of growth and yield of *Miscanthus* in Europe (Swartz, 1993; Lewandowski et al., 2000; Jones and Walsh, 2001; Lewandowski and Schmidt, 2006). *Miscanthus* is sterile requiring vegetative propagation which is expensive;

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therefore the crop must remain productive for several years so that establishment costs can be recovered (Christian and Riche, 1999). It is believed that *Miscanthus* remains productive for 15–20 years (Lewandowski et al., 2000), however we are aware of only one other experiment that has been monitored for long-term productivity (15 years) (Clifton-Brown et al., 2007).

The study reported in this paper initially formed part of the EU *Miscanthus* Productivity Network between 1993 and 1995 (AIR-CT-92-0294) where the objective was to obtain information on the growth and yield of *Miscanthus* in different regions of Europe (McCarthy and Walsh, 1996). When the network study finished the experiment was continued in order to obtain data on its growth and yield in the longer term.

Miscanthus is harvested annually when stems are dead, which is normally in late winter or spring of the following year. At this time mineral nutrient content has been reduced by re-mobilization to rhizomes and natural weathering (which causes leaching from leaves and stems). A low mineral content at harvest is desirable in biomass intended for thermal conversion because it minimises the impact on combustion efficiency and lowers stack emissions. Also it reduces mineral removal in the harvested biomass (offtake) which in turn may lower future input costs and therefore improve production sustainability.

The objective of the experiment which has continued for 14 years was (a) to study the effect of different rates of N fertilizer on growth (1993–2002) and (b) yield (1993–2006) and (c) to obtain information on the mineral content of the biomass at harvest (1993–2002).

2. Methods

The experiment was conducted on Rothamsted Research Farm, Harpenden, Hertfordshire (latitude 51°48′N, longitude 0°21′W, altitude 128 m OD). The soil is a silty clay loam over clay-with-flints of the Batcombe Series (Avery and Catt, 1995). The topsoil, 0–23 cm contains approximately 20% clay and has a pH of 7 (in water). The USDA classification of the soil is aquic paleudalf (Soil Survey Staff, 1992), and the FAO classification is chromic luvisol (FAO, 1990). Rainfall was measured at a weather station located about 600 m from the experiment.

Arable crops were grown at the site between 1988 and 1992. Previously the site had been grassland. Following the harvest of the last arable crop in 1992 the site was left fallow and ploughed in January 1993. Soil was cultivated in April, and in May 100 kg ha^{-1} of phosphorus (P) and 140 kg ha^{-1} of potassium (K) was applied before the soil was cultivated again to produce a seedbed suitable for planting. *Miscanthus* plants produced by micropropagation were planted at 50 cm × 50 cm spacing (4 m^{-2}) in May 1993. The experiment comprised 9 plots each 10 m × 10 m in a randomised block design of 3 replicates of 3 N rates, N0 (control), 60 kg ha^{-1} (N60) and 120 kg N ha^{-1} (N120) applied as ammonium nitrate. The nitrogen was applied annually in spring when shoots were about 15 cm tall usually in April or May, except in 1993 when it was applied in June after planting. Spring application of P and K and herbicides during the experiment are presented in Table 1.

A non-destructive method for measuring crop height and stem number was used between 1993 and 2003. In 1993, five plants on each plot were identified with permanent reference markers and these plants were used each year to maximise the continuity of the data. Stem height was measured from the soil surface to the highest point of the last fully expanded leaf. Measurements were made on between 3 and 12 occasions per year.

Harvestable yield (standing crop biomass) was determined when stems were dead in the winter by cutting and weighing the crop from the inner 6 m × 6 m area of plot. The cut crop was weighed in the field and a sub-sample taken and dried at 80 °C for 48 h to determine dry matter and then used for mineral concentration analysis. The litter was collected on each treatment plot from 3 areas, 1 m^2 and gently washed to remove soil contaminant and dried for the determination of dry matter using the same procedure as for the cut crop. Biomass for mineral analysis was ground to pass through a 1 mm sieve and analysed for N with a LECO CNS 2000 combustion analyser. P and K were determined following digestion in nitric acid and perchloric acid using inductively coupled plasma emissions spectrometry (ICPES).

Table 1 – Fertilizer and herbicides applied to the crop

	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
Fertilizer, kg ha^{-1}														
Phosphorus P	100	–	–	–	–	–	–	58	–	–	–	–	–	
Potassium K	140	116	140	116	140	142	–	290	145	–	–	–	–	–
Herbicides g ai ha^{-1}[a]														
Mecoprop-P	1500 × 2			1500										
Bromoxynil	280 × 2			280										
Ioxynil	280 × 2			280										
Glyphosate				1440									1440	
Clopyralid						100								
Fluroxypyr							200	200		150		100		
Isoproturon		2000												
Paraquat		1000												
Metsulfuron-methyl												1320		

[a] Herbicides applied in 200 l ha^{-1} of water.

Table 2 – Rainfall (mm) and temperature (°C) during the experiment and the difference from the 30-year mean (1971–2000)

Year	Growth season[a]	Dormant season[b]	Annual total	Mean temperature[a]
1993	602 (+206)	286 (−23)	888	12.51
1994	381 (−15)	343 (+34)	724	13.07
1995	227 (−169)	410 (+101)	637	14.09
1996	223 (−173)	291 (−18)	514	12.86
1997	321 (−75)	255 (−54)	576	13.58
1998	551 (+155)	291 (+18)	842	13.11
1999	409 (+13)	305 (+4)	714	13.84
2000	614 (+218)	348 (+39)	962	13.23
2001	527 (+131)	394 (+85)	921	12.73
2002	427 (+31)	448 (+139)	875	13.38
2003	221 (−175)	374 (+65)	595	14.06
2004	479 (+83)	273 (−36)	752	13.83
2005	405 (+9)	219 (−90)	624	13.94
2006	460 (+64)	318 (+9)	775	14.89
30-year average	396	309		13.58

[a] Growth season between 1st April and 31st October.
[b] 1st November–31st March.

Growth, yield and compositional data were analysed for significant differences by analysis of variance (ANOVA) using Genstat (Payne, 2000). No significant pests were found in the crop during the course of the experiment. Barley yellow dwarf luteovirus was identified in the crop in 1993 (Christian et al., 1994) but the impact of the virus on crop productivity could not be measured.

Weed control was important during crop establishment but in subsequent years the effect of the leaf litter layer on the soil surface and the shading effect of the crop canopy reduced the requirement for herbicides to the extent that they were not necessary every year (Table 1).

3. Results and discussion

Miscanthus growth normally started in April or early May, which is the same time as reported in North-East Japan (JIBP Synthesis, 1975) and continued until about the end of October, although, in some years, greenness was present in the stem and upper leaves later into the year. The warmest months of the year coincide with the April–October growth period when mean temperature is 13.58 °C (range 12.51–14.89) (Table 2). The long-term average rainfall for the growth season was 396 mm whilst the average for the study period was 419 mm (Table 2). The wet growing season in 1993, which was the second wettest recorded, probably improved the establishment of the *Miscanthus* that was planted in mid-May. In subsequent years, 1994–1997, the growth season's rainfall was below average but between 1998 and 2006 it was above average except in 2003 which was 44% below the average. Total annual rainfall was above average in 9 years (range +1% to +36% and below average in 5 years (range −10% to −27%). In 5 years, differences from the mean were 10% or less.

3.1. Stem number

Nitrogen rate did not affect stem number and treatment data have been averaged and presented to illustrate the changes over the 10 years (Fig. 1). In 1993, the year the crop was planted; stem number increased throughout the growing season and averaged 32.2 stems per plant at the end of growth (Table 3). When growth started in 1994 stem number was lower than at the end of the previous year but later increased until the end of July then declined until the end of growth. In subsequent years stem number was usually higher in spring than at the end of growth in the previous year and the same growth pattern of increasing stem number in spring followed later by

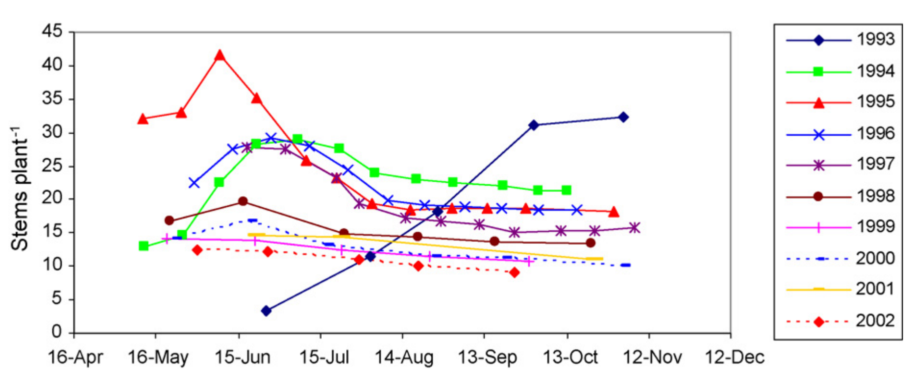

Fig. 1 – Changes in stem number per plant, 1993–2002.

Table 3 – Stem number plant^{-1} at the end of growth each year

N rate/year	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
N0	31.1	24.3	19.1	18.7	17.4	11.7	10.5	9.6	9.4	8.5
N60	33.3	22.1	20.1	20.3	16.3	13.7	11.5	10.1	11.5	8.6
N120	30.2	21.5	17.0	18.0	13.9	12.6	10.3	10.6	11.9	10.5
mean	32.2	22.6	18.7	18.3	15.9	12.7	10.8	10.1	10.9	9.2
S.E.D.[a], d.f. 4	4.23	2.10	2.78	1.69	1.72	0.96	1.04	1.30	1.64	1.25

[a] Standard error of difference.

stem loss was seen each year. It was more pronounced during 1995–1998 than in later years when stem number changed very little over the season (Fig. 1). A reduction in stem number over the season may be an indicator of competition for light and assimilates and possibly affected young plants more because rhizome structure is smaller and contains less assimilate than the rhizomes found in older plants. The decline in stem number through the season was also observed by Clifton-Brown and Lewandowski (2002). With the exception of 1995 and 1996 we found the maximum stem number declined as the plant aged and the final stem number declined from 32.2 per plant in 1994 to 9.2 stems per plant in 2002 (Table 3). The rate of decline appeared to slow as the crop got older but the data do not show whether equilibrium in stem number had been reached by the 10th year.

3.2. *Stem height*

Stem height was not affected by N treatment except in 2002 (Table 4). Stem growth was most rapid in the spring and early summer and maximum height was usually recorded in September or October (Table 4). Only in 1993 and 2001 was stem height increasing at the end of the autumn and stopped by the onset of winter. In some years a small reduction in stem height was recorded in the autumn, and this is attributed to loss of top leaves or leaves becoming less erect. Dry periods during the summer in 1994 and 1995 (monthly data not shown) may have stressed plants and this might account for a small change in height from the early summer period observed in those years and low percentage stem component compared to other years (Table 5). Differences in the date when maximum height was measured are attributed to the effect of seasonal conditions on growth rate. Clifton-Brown et al. (2001a) found no difference in the stem number or stem height of *Miscanthus* during the first 2 years of growth where 60 kg N ha^{-1} or 240 kg N ha^{-1} was applied.

3.3. *Dry matter production*

Biomass yield was first measured in the winter following planting in 1993. Mean dry matter yield that year was low but increased in each subsequent year until 1998 (Table 5). Yield was lower in 1999 and 2000 than in 1998 on all treatments except for the control (0N) in 2000, and yield increased again in 2001 and in 2002, when it was the highest recorded of the 14 successive harvests. Overall, there was no significant effect of N fertilizer on yield. One exception was in 1999 when yields on the N60 and N120 treatments were significantly different from each other, but neither treatment was significantly different from the control. This result cannot be explained and may be due to anomalous values especially since statistical significance was not detected in other years. Since yield in the 10th year was the highest recorded it is possible that maximum yield was reached at this time but the average yield in 2005 was only 9% lower than in 2002. Other studies have reported maximum yield being reached in 2 years in hot environments and 6 years in cool temperate climates (Clifton-Brown et al., 2001b).

Relationships between rainfall, temperature and yield during the growing season were tested statistically and no association was found. The cumulative yields over 14 years from the different N treatments were not significantly different and averaged 178.9 t ha^{-1}. Lack of response to N is attributed to the plant having the C4 photosynthetic pathway which typically has a high nitrogen use efficiency (Brown, 1978), and the effective storage of N in rhizomes. One-year-old plants grown adjacent to this experiment and receiving 60 kg N ha^{-1} contained 162 kg N ha^{-1} (total above and below ground biomass) at harvest of which 45% was in the rhizomes (Christian et al., 2006). A similar amount was found in rhizomes when the plants were two and 3 years old although N content increased by 175% and 202% respectively in these years as a result of increased yield. A lack of response to N

Table 4 – Maximum stem height (cm) and the date when it was measured each year (Rounded values)

N rate/date	3/11/1993	3/10/1994	1/9/1995	18/9/1996	24/9/1997	22/10/1998	19/9/1999	20/9/2000	23/02/2001	24/9/2002
N0	46	141	200	223	284	290	338	346	332	359
N60	44	140	195	209	279	287	335	342	313	347
N120	40	135	185	210	275	294	332	342	326	351
Mean	43	139	193	214	280	290	335	343	320	352
S.E.D.[a], d.f. 4	2.0	11.6	13.8	14.9	4.7	3.5	5.6	3.5	10.6	3.0

[a] Standard error of difference.

Table 5 – Annual dry matter yields ($t\,ha^{-1}$) for the N treatments and the percentage of the yield that was stem (Standing crop, mean of all treatments)

N rate/year	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	1993–2006[a]
N0	1.53	7.30	11.48	13.73	14.34	15.46	14.49	14.51	16.28	16.94	13.72	15.06	16.84	10.53	182.2
N60	1.46	7.09	9.84	11.52	14.09	15.02	14.05	12.38	15.76	18.33	13.22	14.85	15.81	10.08	173.5
N120	1.86	8.01	11.02	12.35	14.76	15.37	14.76	13.73	17.26	17.78	13.66	14.72	15.72	9.90	180.9
Mean	1.61	7.47	10.78	12.53	14.40	15.28	14.44	13.54	16.43	17.69	13.53	14.88	16.12	10.17	178.9
S.E.D.[b], d.f. 4	0.331	0.997	0.558	1.146	0.540	0.322	0.163	0.719	0.540	1.455	1.116	0.837	1.246	0.663	5.92
Stem wt, %	40	83	82	96	97	95	96	98	88	92	–	–	–	–	–

[a] Cumulative total.
[b] Standard error of difference.

in dry matter production agrees with results reported for an established crop of *Miscanthus* in western Germany (Himken et al., 1997). But on a sandy soil previously used for arable crops we found that *Miscanthus* was responsive to applied N (unpublished data) therefore soil type and previous cropping may contribute to crop response to N.

Measurements made during the first 10 years showed that the main component of aerial biomass was stem, except in the first harvest after planting in 1993 when 60% was leaf (Table 5). In the other years the stem component ranged from 82% to 98%; the percentage of stem was not affected by fertilizer N rate. Averaged over the 10 years, 92% of harvestable biomass was stem and this high proportion makes for a higher quality feedstock for thermal conversion, as stem contains less ash and has a higher heating value than leaf (Lewandowski and Kicherer, 1997).

Yield values presented in Table 5 are lower than actual above ground biomass because it does not include the weight of litter or stubble. However, summing litter weight with harvestable yield provides only an indication of total production because litter samples included biomass from previous years that was impractical to separate and some of which was partly decomposed. Between 1997 and 2002 litter weight was fairly constant except in 2000 when it was higher (Table 6) and this probably lowered harvestable yield that year (Table 5), with less leaf attached to the stems. Litter consists mainly of leaves that are dropped after senescence and differences in annual litter weight are mainly the result of the amount of leaf detachment caused by wind before harvest. No significant effect of N treatment on litter weight was detected in any year. Commercial methods of harvesting might recover some of the litter but it can be contaminated with soil, moist and partly decomposed; these factors would adversely affect safe storage and thermal conversion feedstock quality.

The yield profile is similar to that in a 15-year study in Ireland where yield increased until the 6th year, dipped then reached highest yield in the 10th year and then declined again (Clifton-Brown et al. (2007). Another study in the UK where results from three sites were presented as an average, show an increase in yield for the first 4 years before a decline followed by improved yield in the subsequent 2 years (Nixon et al., 2001). These experiments were planted in different years to the study here but show a decline in yield during a mid-period that cannot be age related and is probably a growth constraint resulting from the environment. We saw no evidence of disease. Inter-plant competition may also be a factor but harvestable yield also declines with harvest date further away from the start of senescence (Clifton-Brown et al., 2007) and harvest date is a practical decision. The European *Miscanthus* Productivity Network of which this study formed part, reported yields ranging from 7.7 $t\,ha^{-1}$ to 26.3 $t\,ha^{-1}$ in 3-year-old crops with our results amongst the lowest. The effect of latitude on yield was evident with northern European sites yielding less than those in southern Europe, though some of the southern sites received irrigation (Clifton-Brown et al., 2001b). In our experiment, dry matter yield at maturity is equal or greater than that reported for willow in short rotation coppice in Britain (Lindegaard et al., 2001).

Table 6 – Litter weight ($t\,ha^{-1}$) measured at the harvest of the standing crop

N rate/year	1994	1995	1996	1997	1998	1999	2000	2001	2002
N0	2.45	2.49	4.71	6.22	6.91	6.14	6.31	6.61	5.80
N60	1.99	2.36	4.03	7.04	5.06	5.86	7.85	4.87	4.12
N120	2.41	2.16	4.57	7.0	6.5	6.67	8.39	5.06	6.94
Mean	2.28	2.34	4.44	6.75	6.16	6.22	7.52	5.51	5.62
S.E.D.[a], d.f. 4	0.315	0.483	0.809	0.631	1.477	0.893	1.42	1.035	1.596

[a] Standard error of difference.

3.4. *Mineral content at harvest*

The effect of N fertilizer on N, P and K offtake at harvest was slight. Statistically significant differences were only detected for N content in 1998 where the control, N60 and N120 treatments contained respectively 76 kg N ha^{-1}, 89.0 kg N ha^{-1} and 98 kg N ha^{-1} (S.E.D. 0.81, d.f. 4) and in 1999 when they were 60 kg, 71 kg N ha^{-1} and 83 kg N ha^{-1} (S.E.D. 4.06, d.f. 4). Phosphorus content was not affected by N rate and potassium content was only effected in the year of establishment (1993) when there was a significantly greater content in the N120 treatment compared to N60 and control: 22.9 kg K ha^{-1}, 15.3 kg K ha^{-1} and 16.3 kg K ha^{-1} (S.E.D. 1.19, d.f. 4) respectively. Because few differences were detected, treatment data have been averaged and presented in Fig. 2. Mineral offtake increased between 1993 and 1995 when yield increased most rapidly but in subsequent years the relationship between yield and mineral offtake was tenuous (Table 3 and Fig. 2). The mineral concentration of aerial biomass is at its highest during spring and early summer and then declines, probably as a result of remobilization (Beale and Long, 1997; Christian et al., 1998). Himken et al. (1997) measured the transfer of minerals from leaves and stem to rhizomes to be 21–46% of N, 36–50% of P and 14–30% of K. External influences, such as frost killing leaves and stems stopping re-mobilization, affect mineral concentration at harvest. If the planting year is excluded, the annual variation is quite small for N and P but greater for K (Fig. 2) possibly as a result of rain leaching K from tissue to a greater extent in some years (Sander, 1997). Over the 10 years, the amount of P and K removed at harvest in the biomass was 63 kg ha^{-1} and 886 kg ha^{-1}, respectively. For both minerals, offtake was less than that supplied in fertilizer (Table 1). Our results suggest that fertilizer rates of about 7 kg P ha^{-1} yr^{-1} and 100 kg K ha^{-1} yr^{-1} would anticipate future yield potential as well as replenish soil reserves, but further investigation is required to confirm this. The rate of K proposed is in agreement with that suggested by Lewandowski and Kicherer (1997).

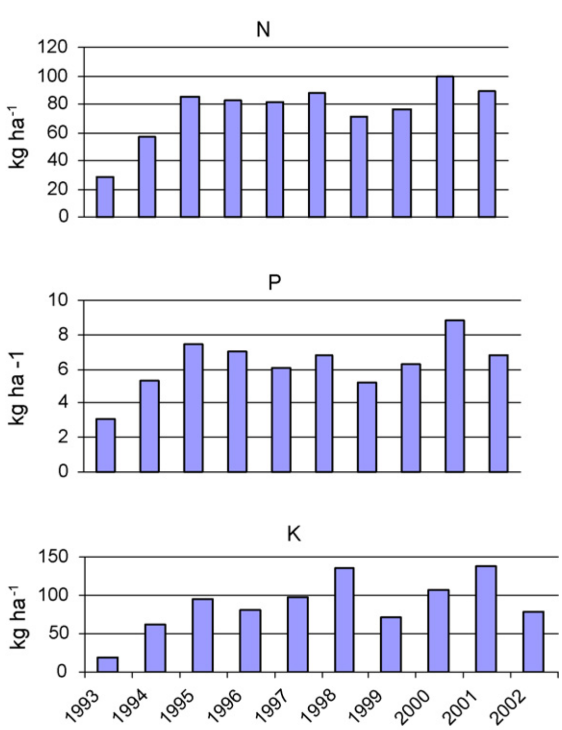

Fig. 2 – Offtake of N, P and K in harvest biomass, 1993–2002.

In 1998 the biomass was analysed for fuel quality characteristics and found to be a suitable fuel for use in a modern combustion plant (Christian and Riche, 1999).

Gross N balances for the treatments are presented in Table 7. N offtake totalled for the first 10 years was not significantly different between treatments and averaged 758 kg ha^{-1}. For the control treatment, N removed at harvest came entirely from soil sources plus atmospheric deposition and for N60 offtake exceeded N supplied as fertilizer by 24%. For the N120 treatment, fertilizer applied greatly exceeded offtake and resulted in higher losses from winter leaching than the other treatments (Christian and Riche, 1998); however, leaching losses were less than would be expected under winter cereal crops (Goss et al., 1993). Budgets do not include N in litter, roots and rhizomes because the N they contain is in a transitional phase within the soil N reserve. N lost in the form of gaseous N_2O-N probably occurred on plots, particularly those that received N fertilizer; Jorgensen (1997) measured losses equivalent to 1.5% of the 75 kg N ha^{-1} applied to *Miscanthus* growing on a sandy soil. The loss was more than double the loss from an adjacent crop of rye (*Secale cereale*) and was explained as the effect of the untilled soil and the litter layer maintaining a higher soil water content that would promote N_2O production.

The annual removal of N by the crop in the N0 treatment (mean 69 kg N ha^{-1} yr^{-1}) is consistent with the N supply from a silty clay loam soil at Rothamsted having grass and arable crops in its recent history (Cooke, 1965; Macdonald et al., 1997), supplemented by aerial deposition of N (Goulding et al., 1998), and the amount removed is similar to the requirement for *Miscanthus* calculated to be 50–70 kg ha^{-1} yr^{-1} by Himken et al. (1997). As no yield response to N fertilizer was observed there is no case for applying N to *Miscanthus* in the 14 years after

Table 7 – Gross nitrogen balances for *Miscanthus* receiving three nitrogen treatments, 1993–2003

Inputs, kg N ha^{-1}	N0 (control)	N60 (60 kg ha^{-1} yr^{-1})	N120 (120 kg ha^{-1} yr^{-1})
Fertilizer	0	600	1200
Aerial deposition[a]	433	433	433
Total	433	1033	1633
Outputs, kg N ha^{-1}			
In crop	687	743	843
Winter leaching[b]	224	267	629
Total	911	1010	1472
Difference between input and output	−478	−23	+162

[a] Goulding et al. (1998).
[b] Christian and Riche (1998), Christian and Riche (2000) and Christian et al. (2003).

planting in this situation. On soils having lower fertility and less aerial deposition, it may be necessary to apply N. In commercial practise it would be prudent to test for N response every few years in plots within the crop to ensure that there is no unrealised yield. However, in view of the high fossil fuel emissions associated with the manufacture of N fertilizer (Patyk and Reinhardt, 1997), it is desirable to minimise N applications. Occasional applications of organic manure would be a possible means of ensuring a continuing supply of N and other nutrients. As far as we are aware, the timing of N application to *Miscanthus* has not been investigated and it is normally applied in the spring as growth commences (Lewandowski et al., 2000). Himken et al. (1997) described how early growth used N and other mineral nutrients stored in the rhizome. The explanation for this is that root is only functional for 1 year and new root does not form on new rhizome (which produces stem growth) until about 1 month after stem growth begins (JIBP Synthesis, 1975).

Therefore applying N at the start of growth may not be appropriate and could result in N losses. Christian et al. (2006) found that only 38% of ^{15}N-labelled fertilizer applied in spring to a 1-year-old crop was taken up by the plant although N recovery by a more established crop was greater.

4. Conclusions

Miscanthus × *giganteus* can be successfully cultivated over several years on a silty clay loam soil in Southern England and the reliability of the crop in a supply chain is enhanced by the absence of pests and low levels of disease present.

Dry matter yield, measured on dead stems standing in winter, increased for the first 6 years of growth, was lower for 2 years then increased again. Heaviest yield was measured in the 10th year and it is not clear whether maximum yield has been determined.

There was no yield response to nitrogen fertilizer. The lack of response results from soil type, previous cropping, the plant having a C4 photosynthetic pathway and the natural recycling of N (and other minerals) from stems and leaves into rhizomes at senescence and process reversal in the following spring to support early growth.

N fertilizer rate did not affect P and K content in the established crop at harvest and the total amounts of each that were removed was less than the amount applied as fertilizer during the experiment. Fertilizer rate should anticipate future yield expectation and compensate for offtake to prevent depletion of soil reserves. The rate and timing of fertilizer application requires further investigation on a range of soil types.

Pesticides were not necessary every year and, taken with fertilizer requirement, the results of this study indicate that *Miscanthus* is sustainable for at least 14 years on this soil and in this environment and can be considered as a low input crop having a low environmental impact.

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