MAFF

MINISTRY OF AGRICULTURE, FISHERIES AND FOOD

RESEARCH AND DEVELOPMENT - FINAL PROJECT REPORT

NF0403 - MISCANTHUS AGRONOMY (FOR FUEL AND INDUSTRIAL USES)

SCIENTIFIC REPORT

Name and address of contractor Dr M Bullard ADAS
Tel: 01354 692 531 Fax: 01354 694 488

MAFF Project Officer - Dr Donal Murphy-Bokern Tel: 020 7904 6779 Fax: 020 7904 6801

MAFF - Agri-Industrial Materials section – www.maff.gov.uk/farm/acu/acu.htm

GENERAL INTRODUCTION

This report describes research undertaken into the agronomy of the novel energy crop, agricultural, the other environmental. There is surplus agricultural land available in the UK and Europe; currently 10% of arable land must be set-aside from food production under Common Agricultural Policy regulations (Agenda 2000). Certain energy crops, including miscanthus, are now eligible to be grown on set-aside land, and thus may provide added value to the farmer if the economics are attractive. The market for energy crops is now developing in response to the need for atmospheric CO_2 abatement. The UK government identifies biomass-derived energy as one of the main ways that it can achieve its obligations under the Kyoto Climate Change Agreement (DTI, 1999). Under this agreement, 10% of the UKs electricity is to be generated from renewables by 2010, in order that we reduce anthropogenic CO_2 output by 12.5% and all global warming gases by 20% relative to 1990 levels. As a consequence, the government now aims to generate 500 to 1000 MWe from biomass by the year 2010, an undertaking that might require as much as 125,000 ha of land (DTI, 1999; D Hunter, pers. comm.). The current project was undertaken with these policy objectives in mind. Throughout the lifetime of the project, the dual MAFF objectives of identifying productive alternative uses for set-aside, and supporting the development of viable biomass energy systems were met.

Much activity has focused on the development of relatively high yielding, low-maintenance perennial plant species as energy crops, and the first short rotation coppice-powered stations are now being built. During the early 1990s, the Asian perennial C4 grass Miscanthus was identified as offering, theoretically, the attributes of the ideal energy crop (Anon., 1991; Rutherford & Heath, 1992). Namely, high dry matter yield, perennial growth, efficient conversion of radiation to biomass, efficient use of nitrogen, efficient use of water and good pest and disease resistance.

The growth pattern of these grasses in northern Europe is relatively simple. Rhizomes or tissue-cultured plants are planted during late April and May, multiple shoots appear and grow rapidly once maximum daytime temperatures exceed approximately 10°C. Growth during May, June and July is extremely rapid, producing cane like stems which may reach 3m in height. Once full radiation interception is achieved by the canopy, the lower layers of leaves begin to senesce, whilst stem growth continues through August and September and even into October. Full senescence occurs following the first frosts of the autumn. During the end of the growing season nutrients are re-mobilised from stems and leaves to the rhizomes. The standing stems gradually dry throughout the winter, until by February or March the crop is ready for harvest.

The crop can be harvested either by cutting/conditioning, swathing and then baling the stems or by chipping using a forage harvester. The early spring, between harvest and initiation of re-growth, is the ideal time for weed control. New shoots appear in March-May. Thus, an annual cycle of biomass harvest is achieved with this crop. The forms of Miscanthus currently grown for biomass (*Miscanthus sacchariflorus* and *M. x giganteus*) seldom flower in the UK due to their short day length requirement and possibly an accumulated thermal time requirement. Many other species, however, notably the many varieties of *M. sinensis*, do readily flower in the UK.

The general description of agronomy above, was based on information that has been assimilated throughout the current project's duration. In this project ADAS undertook to determine whether this genus of grass had potential as an energy crop for the UK. At the onset of the project in 1992, nothing was known of the performance of this species under UK conditions. The research reported here consisted of two major experiments; a seven site study of the yield potential of *Miscanthus sacchariflorus* and a physiological examination of *M. x giganteus*.

In addition, a summary of an economics and markets review was undertaken (Annex III). These pieces of work are summarised in a manner that is consistent with the major experimental objectives detailed in the next section.

METHODS, RESULTS AND IMPLICATIONS

Objective 1. - to quantify the potential and medium/long-term viability of Miscanthus as a biomass/energy crop.

The central hypothesis tested under this objective was that miscanthus will survive under temperate conditions, and yield economically significant quantities of biomass. Central questions were: Could miscanthus survive in the UK? Could high yields be attained and maintained? What was the most appropriate planting density for the crop? In 1992, in order to answer these questions, three sites of inherent high productivity potential for C4 crops were selected (ADAS Arthur Rickwood, ADAS Rosemaund and Buckfast Abbey), having grade I land, high annual radiation receipts and relatively high spring temperatures. For convenience these sites are subsequently referred to as ‘original’ sites. Ten plots were established, by hand, from a common stock of rhizome cuttings from *M. sacchariflorus* plants, at a density of 4 plants m^{-2}, in March 1992. Five plots were thinned to a density of 1 plant m^{-2} following the first harvest in winter 1992/93. Fertiliser was applied, each spring, at 60 kg ha^{-1} N and 75 kg^{-1} of both P_2O_5 and K_2O.

An additional four ‘new’ sites were established during spring 1994 at ADAS Bridgets, ADAS Boxworth, ADAS Gleadthorpe and ADAS High Mowthorpe. These sites were selected because it was expected that they would present at least one limitation to maximum yield expression in a C_4 crop such as Miscanthus. Specifically, moisture supply stress at Gleadthorpe, temperature/exposure/high pH at High Mowthorpe, high pH at Bridgets and a clay soil subject to waterlogging in winter at Boxworth. Growth characteristics throughout the season were recorded, and biomass yield assessed each winter, by hand harvesting a 36 m^2 area in each plot. Site details are provided in Table 1. Results at the original and new sites were not directly comparable because of differences in establishment year. However, trends where detected, are discussed.

Miscanthus survival and growth characteristics:

Initial establishment was above 90% for all sites except Buckfast Abbey (70%), where high failure was probably due to late planting (June rather than April). Following the establishment year, losses were never greater than 3%. Thus the maritime climate of the UK does not appear to induce the winter losses caused by unfavourable conditions seen continental Europe (Schwarz et al, 1995, Walsh, 1997). M. sacchariflorus is a native of wet/semi-aquatic habitats in China and Japan (Matumura & Yukimura, 1975; Osada, 1993) and this may explain the crops ability to tolerate winter waterlogged conditions. The late planting loses at Buckfast Abbey emphasise the need for early planting and keeping rhizomes moistened prior to planting.

Shoot emergence date varied greatly between sites and seasons. Average emergence dates were at one extreme the end of March (ADAS Arthur Rickwood) and at the other the end of April (ADAS High Mowthorpe). Early spring-time plant development was slow. As much as one month separated shoot emergence from the date that the first leaf unfurled from the sheath. Earlier emergence did not necessarily confer an advantage to the crop, because in most years early spring canopy re-growth was destroyed by near-zero air temperatures, such that effective growth did not begin until May in most years. The impact of this shortened growing season on yield could not be calculated, but it will be important to develop more cold tolerant varieties if the crop is to become a commercially viable option for farmers. Correlation between emergence date and accumulated temperature failed to identify any relationship across sites.

At the original sites, crops attained heights in excess of 2.5 m after the first year and equilibrium stem densities of 50-70 (Figure 1). From the second season onwards, early spring stem production was typified by over production followed by self-thinning of stem numbers as competition for light resources increased. As the experiment progressed the difference between stem density per unit area between the two original populations declined and by 1998 there were no differences in stem density between populations. The quantity of stems maintained at equilibrium is still increasing (Fig. 1a). This information could provide a mechanism in future years for rapid determination of the speed with which a miscanthus crop achieves maturity. Crop height development was closely correlated with temperature accumulation above 6°C, the baseline below which leaf extension ceases in miscanthus (Beale & Long., 1995). At the new sites, morphological development mirrored that at the original sites, although progress to maximum height and stem number was protracted. Crop heights were significantly lower than those at the original sites for any given stand age, and some (Gleadthorpe and Mowthorpe) were distinctly poor. Equally, stem densities at high Mowthorpe were also much lower than at the other sites.

Table 1. Details of experimental sites

ADAS Farm	County	Soil type	altitude	annual rainfall (mm)
Original Sites				
Arthur Rickwood	Cambridgeshire	Peaty loam	-3m	548
Buckfast Abbey	Devon	Sandy clay loam	50	1,350
Rosemaund	Herefordshire	Silty clay loams over old red sandstone	84	711
New Sites				
Boxworth	Cambridgeshire	Calcareous clays over chalky boulder clay	58	559
Bridgets	Hampshire	Chalky silty loams over chalk	91	807
Gleadthorpe	Nottinghamshire	Loamy sands over bunter sandstone	60	610
High Mowthorpe	North Yorkshire	Chalky silty loams over chalk	195	750

Miscanthus yields:

At the original sites first year yields were between 1.8 and 6.7 odt ha^{-1}. Yield at Buckfast Abbey was suppressed due to the late planting, and this effect was carried through to the next season where yield was depressed compared to the other two sites. The average yield from high planting density, excluding the establishment year, was 18 odt ha^{-1}. Distinct differences could be seen in crop yields between densities in the first three years (Table 2). Highest yields at Rickwood, Rosemaund and Buckfast Abbey were 24.4, 19.2 and 20.5 odt ha^{-1}, respectively. These occurred in different seasons. Summer moisture supply was a key determinant of yield, although the results indicate that 20 odt ha^{-1} yr^{-1} is achievable at fertile sites in years where moisture is not limiting. This is significantly higher than the anticipated threshold for viable energy crop production, which is commonly set at 12 odt ha^{-1} yr^{-1} (Heath et al., 1995), and higher than most expectations for currently grown coppice varieties, and it indicates that miscanthus would be a viable alternative energy crop. Within a site, crop height could be used as a crude indicator of expected final yield. Yield at the original sites, from 1994 onwards, was significantly related to accumulated temperature above a base of 6°C ($P=0.03$, $R^2=0.82$). The slope of the relationship (yield = 0.0113. Tsum) indicated that an additional oven dry tonne would be produced for every additional 88 accumulated degree days.

An independent regression analysis of all new sites from 1996 onwards indicated that productivity at these sites was also related to accumulated temperature above a base of 6°C, with a virtually identical slope ($P=0.014$, $R^2=0.65$). Use of this baseline data may prove useful in determining the optimal cropping areas for miscanthus.

Table 2. The comparative total dry matter yields of Miscanthus sacchariflorus established at two plant densities at seven sites in England.

Site	Density (plants m^{-2})	Dry matter yield (stems plus leaf litter) at harvest ($t\ ha^{-1}\ yr^{-1}$)						
		1992/3	1993/4	1994/5	1995/6	1996/7	1997/8	1998/9
A Rickwood	1	--	16.5	15.3	11.0	16.6	20.7	20.2
	4	6.7	24.4	18.2	12.4	17.1	20.9	20.4
Rosemaund	1	--	6.3	13.9*	15.4*	18.5	16.7	24.7
	4	6.0	15.8	13.2*	18.5*	16.7	17.5	24.0
Buckfast Abbey	1	--	2.7	10.1	17.5	20.8	16.5	19.2
	4	1.8	11.9	19.7	20.5	19.6	16.4	19.7
Boxworth	1			0.8	1.7	5.9	14.9	12.2
	4			0.2	6.1	10.1	17.5	14.2
Bridgets	1			0.4	5.0	11.6	16.5	18.7
	4			1.1	10.7	18.8	22.2	17.4
Gleadthorpe	1			0.2	1.9	4.4	13.2	12.6
	4			1.0	2.5	4.8	13.4	12.2
High Mowthorpe	1			0.2	0.6	1.7	4.0	10.1
	4			0.8	2.7	7.5	12.9	12.8

Note:

Yearly sequence. - for example, 1992/3 refers to a crop that grew in 1992 and was harvested in March 1993.

Leaf litter component estimated at 20% of standing crop

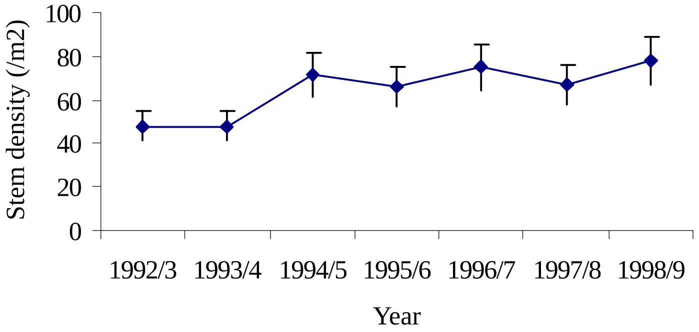
Of the new sites, two groups could be distinguished. Sites in the first group (high potential; Boxworth and Bridgets) appear to show a similar yield potential to the original sites yet take longer to achieve that potential, whereas those sites of low potential (Gleadthorpe and Mowthorpe) express relatively low yields due to climatic limitation. The yield progress of the three groups (Figure 2) indicates that there was no significant increase in yield after the second season at the original sites, whereas for both the high potential ($P=0.003$, $R^2=0.86$) and the low potential ($P<0.001$, $R^2=0.95$) new sites, there continues to be a strong positive relationship between age and yield. Across the five seasons, the high potential sites have increased yield at an average rate of 4.1 odt ha^{-1}, whereas the low potential sites have increased yield at a rate of 3.4 odt ha^{-1}. Miscanthus at ADAS Gleadthorpe and ADAS High Mowthorpe may be on the margins of economically viable yield, although while yields are still increasing annually we cannot know this for sure.

Two components of miscanthus growth could be identified; the yield building phase which may last 2-5 years, and the equilibrium phase, during which highest yields are maintained. To summarise, most of the arable sites studied have demonstrated that they are capable of producing high quantities of miscanthus biomass and of maintaining this yield through time. The major differences between sites were due to the duration of the yield-building phase.

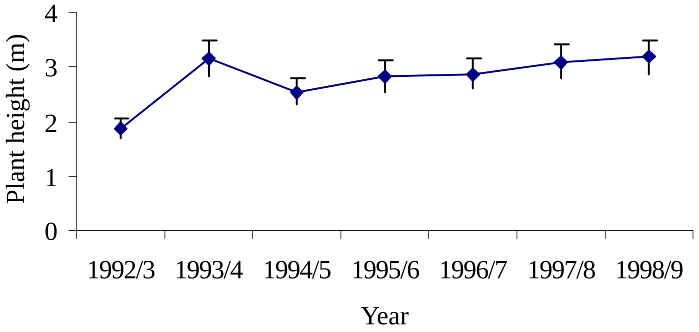
Moisture availability and low temperature are the main causes of yield limitation. We have not yet been able to quantify the duration of the equilibrium phase.

Figure 1. Average growth characteristics of M. sacchariflorus growing at the 'original' sites

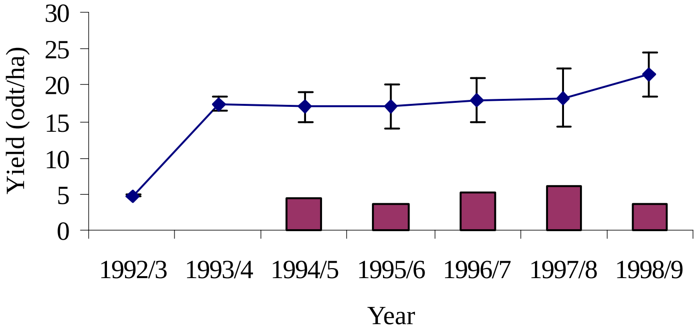
a) stem density (stems m^{-2})



b) plant height (cm)

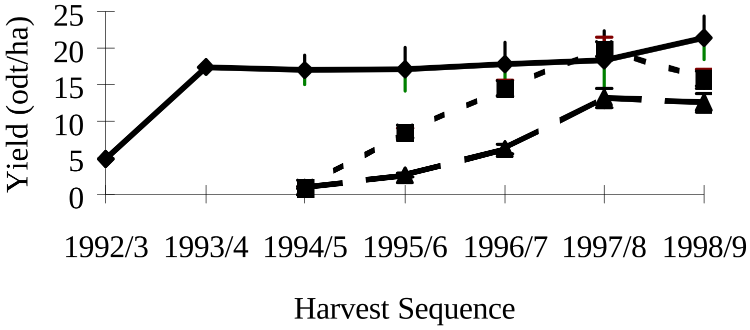


c) Total crop yield (odt ha^{-1}) and leaf litter yield (odt ha^{-1} – vertical bars)



The contribution of leaf litter to total yield was high, and varied from site and season. Average contribution of leaf litter to the original sites was 22% ±3 (Fig 1c.). The contribution of leaf litter at the new sites was higher, on average 29% ±5. This reflected the younger age of the crops – smaller plants, and thus lower yields, tended to be comprised of proportionately more leaf. In other words, plants invested in proportionately more leaf production than stem extension. However there was not a strong statistical relationship (r^2 = 0.15).

Figure 2. Yield progress of three classes of M. sacchariflorus, grouped by age/yield class. Original sites (◆), new sites with high potential (■) and new sites with lower potential (▲). Vertical bars represent standard errors.



Standing crop moisture content generally declined following senescence, although the moisture content at harvest was seen to vary considerably between sites seasons, from 35 – 70% (w/w). A number of factors were implicated:
Practicality of harvest. In many instances the miscanthus crop was harvested during the first available weather window, before the crop had dried down fully.
Leaf material. There was significant variation in the amount of leaf material remaining on stems in different seasons. Leaf material had a lower moisture content than stems.
UK climate. High rainfall and humidity during winter in the UK indicate that moisture contents below 50% may not be achieved unless some form of stem conditioning is undertaken.

At each harvest the percentage nitrogen, potassium and phosphate in free-standing stems (including retained leaf) and leaf litter was measured (Table 3). Nutrient content in standing stems could be considered the quantity removed from the site whilst leaf litter would predominantly remain on site and the nutrients would be re-cycled. A number of trends in the data were apparent. Proportionately more nitrogen (1.04%) was retained in leaves than in stems (0.65%). Conversely, more potassium was retained in the stems (0.70%) than in leaves (0.30%). Very low concentrations of phosphate were retained in either stem or leaf. There was some variation in the magnitude of the amount on N in stems between seasons at many sites, with higher N contents (as much as 1.5%) in some instances. This was probably related to the proportion of leaf retained on the stem, which although not measured directly, was seen to vary between years. In particular, more leaf was retained at the end of the first year, giving higher N off-take figures. The nitrogen content of biomass should not exceed 1% in gasification systems (Lewandowski & Kicherer, 1997). Thus, the UK miscanthus crop is, on average, within this threshold. However, first year biomass yields may exceed this threshold, and considering the low yield (2-7 odt ha^{-1}) attained in the first season, it may be prudent not to harvest until year 2. The effect of this delay in harvesting on the economics of production are minimal (see objective 4).

From the nutrient content data we can deduce that a miscanthus stand of 18 odt ha^{-1}, consisting of 25% leaf litter, would generate the nutrient off-take and soil return figures shown in Table 4. A small, as yet unquantified, component of the leaf litter will be harvested, as discussed earlier, thus the effective off-take will be slightly higher than the stem based prediction alone. However, these off-take figures for N are extremely low. The potassium off-take may be more worrying, although potassium tends to reside in fuel ash rather than being emitted into the atmosphere as is the case with nitrogen. The leaf litter not only returns nutrients but also suppresses weed competition by forming a mulch.

Table 3. Stem and leaf nutrient content (% w/w) at each of the seven sites, expressed as a mean for all seasons.

	Stem nutrient content (%) averaged across all seasons			Leaf-litter nutrient content (%) averaged across all seasons		
	N	K	P	N	K	P
Rickwood	0.72±0.04	0.85±0.20	0.04±0.01	1.10±0.08	0.31±0.07	0.06±0.01
Rosemaund	0.62±0.04	1.42±0.07	0.06±0.01	1.20±0.02	0.35±0.07	0.06±0.01
Buckfast Abbey	0.44±0.04	0.62±0.06	0.03±0.01	1.10±0.07	0.19±0.05	0.07±0.01
Boxworth	0.57±0.02	0.60±0.10	0.05±0.01	0.86±0.02	0.18±0.02	0.04±0.01
Bridgets	0.42±0.04	0.21±0.06	0.02±0.01	0.85±0.04	0.12±0.01	0.05±0.01
Gleadthorpe	1.12±0.20	0.66±0.16	0.27±0.15	1.20±0.07	0.50±0.17	0.03±0.02
High Mowthorpe	0.67	0.56	0.06	1.0	0.46	0.07
Grand Mean	0.65	0.70	0.08	1.04	0.30	0.05

Table 4. Nutrient off-take (kg ha^{-1}) for an 'average crop' consisting of 18 oven dry tonnes (odt) of biomass of which 25% is leaf litter.

	Stem-based nutrient off-take (kg ha^{-1})	Leaf litter-based nutrient off-take (kg ha^{-1})
N	88	47
K	95	14
P	11	2

What is the correct density to grow miscanthus?:

The optimal planting density will combine maximum crop packing to achieve the highest yield, with the minimal number of plants to keep establishment costs low. Because the miscanthus rhizome gradually spreads in the available soil space, the low initial density crop took between 3 and 5 years to achieve a similar yield to the high density, suggesting that in some instances a planting density of 40,000 plants ha^{-1} is unnecessarily high. Equally, 10,000 plants per hectare is too low to combine rapid progress to the yield optima in all situations. It is therefore suggested that the optimal crop density is 20,000 plants ha^{-1} is proposed for commercial plantings.

Can miscanthus be established in more challenging conditions?:

Establishment of the crop in more challenging conditions increases the length of time needed for a yield optima to be reached; in the new sites the optimum may have been attained after 4 seasons rather than two. The evidence reported for the seven site study indicates that miscanthus can be grown on a wide range of lowland soils, from clays to silts and loams.

The major limitations to yield will occur when moisture is not retained in the soil profile or where the growing season is constrained by low temperatures. Thus Gleadthorpe and High Mowthorpe, respectively, have been seen to yield at the low end of the spectrum for the crop. It is unlikely that harvested yields (i.e. excluding leaf litter) from established crops on any uncontaminated arable land (grades I-III) south of a line drawn from the Severn to the Wash will be less than 12 odt ha^{-1} yr^{-1}. Many can be expected to produce 15 odt ha^{-1} annually. It is anticipated that these figures could be revised upwards as progress with the selection and breeding of more suitable varieties takes place.

Objective 2 - to continue physiological studies of Miscanthus x giganteus in order to determine the degree to which the crop functions as an efficient C_4 crop under temperate conditions.

The hypothesis underlying this work, funded for the period 1993-1996 under the MAFF/ADAS Seedcorn arrangement, was that miscanthus C_4 metabolism functions efficiently under temperate conditions, and this is manifested through high radiation use efficiency and yield (Bullard, Heath & Nixon, 1995; Beale & Long, 1995). In order to test this hypothesis, micro-propagated M. x giganteus was planted at ADAS Arthur Rickwood on 17 May 1993. Two crop densities were established; 4 plants m^{-2} (high density) and 1.78 plants m^{-2} (low density). Detailed measurements of radiation interception, leaf area development, below and above-ground biomass production and plant tissue nutrient content were taken each season.

General patterns of growth in *M. x giganteus* were similar to those of *M. sacchariflorus*. Maximum crop height was 2.8m, considerably less than that of *M. sacchariflorus* growing at the same site. Differences in height between density declined as the crop matured. Height development tracked canopy development and radiation interception, with interception occurring earlier each season as the stand 'matured' and occupied the available space more rapidly. Initial springtime stem densities peaked at between 100 and 170 stems m^{-2}. As with *M. sacchariflorus*, canopy closure and thus competition for light, triggered self-thinning in both densities so that 60-80 stems m^{-2} survived past canopy closure.

Table 5. Crop growth characteristics for *M. x giganteus*.

Year	Crop height (m)		Peak stem density (stems m^{-2})		Equilibrium stem density (stems m^{-2})	
Crop Density (plants m^{-2})	4	1.78	4	1.78	4	1.78
1993/4	176	132	158	104	141	104
1994/5	195	171	104	66	64	58
1995/6	184	186	167	72	86	45
1996/7	280	170	149	151	86	71
1997/8	283	275	148	65	80	59

Differences in the morphology of the crop diminished as the crop aged. For example, by the fourth season the difference in radiation interception at any given point was less than 5%. Crop canopy development, measured as leaf area index (LAI), indicated that for a fully effective canopy, a LAI of 5-6 must be achieved. The highest LAI achieved was 8.6, during 1997. The main constraints to leaf area development were low springtime temperatures and drought. High planting density consistently produced higher LAI and canopy duration although from 1995/6 onwards this was not translated into a significant yield advantage. It was found that this was because the leaves at the high plant density were orientated in a less efficient manner. We found that canopy closure of a mature (years 3+) stand can be expected to occur at mid July and that this full canopy remains in place until the first autumnal frost.

The seasonal peak in biomass productivity increased year on year throughout the experiment (Table 6), perhaps suggesting that *M. x giganteus* required more time to achieve maximum yield expression than *M. sacchariflorus*. However this could not be confirmed because the experiments were set up in different seasons. Harvested yield capacity appeared to be lower for *M. x giganteus*, and this is important because this species represents most of the commercially available planting material in the UK. The peak biomass yields from each summer are presented in Table 6. These figures were greater than final harvested yield due to leaf loss during autumn. On average, 67% of the mid-summer standing crop biomass component was from stems. Below-ground biomass increased annually to an equivalent of approximately 10 odt ha $^{-1}$ in the fourth year.

Table 6. Peak above ground productivities (odt ha^{-1}) for *M. x giganteus* growing at two densities, 1993 – 1998.

Plant Density	Above ground productivity (t ha^{-1})					
	1993/4	1994/5	1995/6	1996/7	1997/8	1998/9
4 plants m^{-2}	7.7	15.0	15.5	19.5	24.5	18.8*
1.78 plants m^{-2}	3.5	11.0	16.0	16.0	23.5	14.2*
Mean	5.5	13.0	16.8	17.8	24.0	

*Incomplete season data available. Final measurement made in late July.

The key characteristic of a crop that demonstrates how efficiently it is growing is its radiation use efficiency (RUE); which shows the amount of biomass created by the canopy interception of a unit of solar radiation. Normal (so called C$_3$) crops in the UK have a photosynthetic efficiency threshold of 2.6 g MJ^{-1} m^{-2}, whereas C$_4$ crops such as miscanthus and maize should be able to significantly exceed this efficiency under ideal conditions (Monteith, 1977). Table 7 shows that contrary to expectation and previous studies (Beale & Long, 1995; Walsh, 1997), *M. x giganteus* photosynthesis does not function more efficiently than other crops in the UK. The lower efficiencies may have been seen because the crop was under severe moisture stress during 1995 and 1996. Nonetheless, *M. x giganteus* was capable of demonstrating high yield. High yield was achieved by efficient capture of radiation from early July to October each year and reinforces the need to develop varieties that do not suffer low-temperature induced loss of canopy in the spring.

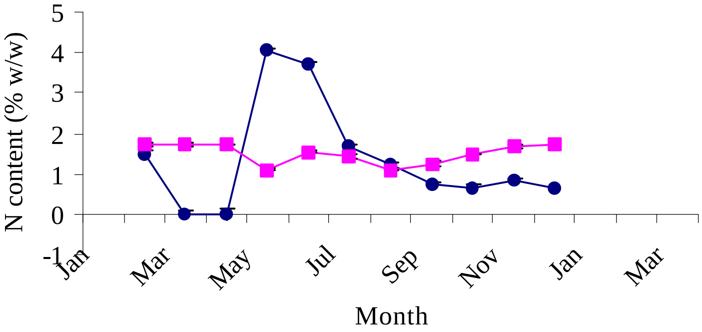
Table 7. Radiation Use Efficiency (g MJ^{-1} PAR m^{2}) for above-ground M. x giganteus growing at two densities, 1993 – 1998.

Plant Density	Radiation Use Efficiency (g MJ^{-1} PAR m^{2})					
	1993/4	1994/5	1995/6	1996/7	1997/8	1998/9
4.0 plants m^{-2}	2.34	2.24	1.70	2.10	1.86	2.09
1.78 plants m^{-2}	1.42	1.96	2.32	1.56	1.68	1.63

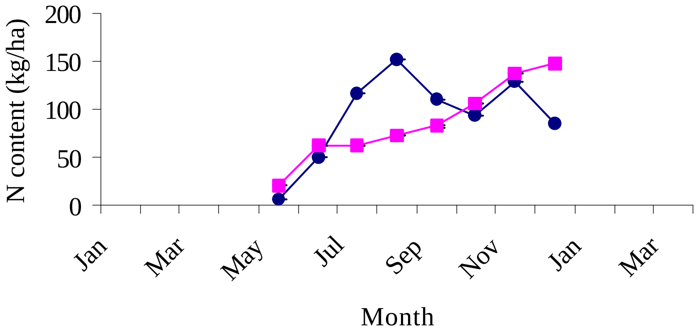
The internal cycling of nitrogen in a typical season (Figure 4) showed that rapid mobilisation from root to shoot, as a percentage contribution to shoot tissue, occurs early in the season after which the percentage concentration declines. However, the gross nitrogen content in above-ground tissue increases linearly to 150kg ha^{-1}, coinciding with canopy closure and an LAI of 5, indicating that miscanthus requires approximately 30kg N for each unit of green leaf area produced. In the autumn the N content declines rapidly. Throughout the season the N concentration in the rhizomes remains relatively static, although there is a continual accrual of nitrogen by weight as the rhizome grows and as N recovery from the soil is augmented by N re-mobilisation from shoots (Christian et al, 1997; Christian pers. comm.). By the end of the second growing season the concentration of nitrogen in the standing crop is half that of the preceding crop.

Figure 4. Seasonal acquisition of nitrogen by below ground (■) and above ground ( ) plant organs:

a) nitrogen as a percentage of plant weight



b) total nitrogen yield (kg/ha)



Patterns of nutrient off-take and quantities removed, were similar for Miscanthus x giganteus and *M. sacchariflorus*. A substantial quantity of nitrogen is re-translocated to the rhizome during the autumn, indeed Christian et al. (1997), working with the same species, indicate that up to 90% of above ground N is rhizome derived. Assuming 150kg N ha^{-1} is held in the crop canopy during the height of summer, this means that the miscanthus crop requires 15 kg N ha^{-1} from non-rhizome sources. This will be supplied from residual soil supplies particularly as 47kg N ha^{-1}, on average, will be returned to the soil annually as leaf litter. Our study suggests that the crop could be harvested from November onwards with no significant increase in the percentage N content. A November harvest would significantly improve the recovered crop yield, since at least 30% of peak biological productivity is lost prior to winter harvest. This would also aid harvesting, allowing easier trafficking and windrowing to reduce stem moisture content, and may well improve feedstock quality. This is an important observation which should be further tested in the field.

Objective 3 - to identify problems with the establishment and maintenance of Miscanthus in large-scale field experiments, and develop guidelines for field-scale commercial production.

A general picture of the husbandry requirements of the crop in the UK has been obtained, and this information has already been presented in the introduction. We have demonstrated in these studies that miscanthus can be established either from rhizome cuttings or micro-propagated plants, and that miscanthus can successfully over-winter in the UK. Of the two techniques, we expect production from rhizomes to be more economically viable and also more likely to lead to effective establishment. This is in contrast to central European experiences (Schwarz, Murphy & Shnug, 1994) where unfavourable winter conditions have caused extensive losses. However, all crops reported in the current study were established by hand. There is currently no research work on mechanised planting, but it is anticipated that the move from hand planting to mechanical planting will require a significant investment in research.

One of the key limitations for the crop appears to be yield recovery. It has become clear that accessibility to land for harvest during February or March may present significant problems in some years. Also, the moisture content of harvested biomass will in most seasons be higher than desired due to prevailing climatic conditions. In the previous section we have described research results which indicate that recovered yield could be increased by 20-30% by harvesting in November with little significant increase in the percentage N off-take. Some anecdotal evidence suggests that the crop can be cut and dried in rows, even in March, to reduce moisture content to 20%. This requires further research.

Pests and diseases have not been a problem in the current study. However, two potential pests, the common rustic moth (*Mesapamea secalis*) and ghost moth (Hepialis humili) have been identified (Nixon, 1997) feeding on the crop. The common rustic moth larvae cause damage to developing shoots during spring, although levels of incidence have not yet exceeded 1% of emerged shoots. The ghost moth larvae feed on miscanthus rhizomes but have been observed only at very low incidence. Both species appear to have migrated from their normal grassland hosts. Although there was no evidence of any yield loss due to these insects it is essential that their activity and occurrence are monitored if miscanthus is to be grown on a wide scale, particularly if it is subsequently found that miscanthus is suited to soils coming out of permanent grassland production. There is no evidence yet to support yield predictions on ex- lowland grassland, and this should be a prime research objective for the future.

Weed control after the first season was achieved effectively using a pre-shoot emergence application of glyphosate in the spring to control grass weeds. Dicot weeds were generally ‘smothered’ by the rapid springtime growth. Establishment season weed control was effected using a combination of mechanical and chemical methods. The crop is very sensitive to weed competition at this stage, although there are many options for weed control (Bullard et al., 1995). Stem basal diseases (*Fusarium spp*.) have been noted at a number of sites, and at Buckfast in 1997/8 contributed to loss of yield through stem basal lodging. The incidence of such pathogens may be related to autumnal rainfall. Further monitoring should be carried out. Other areas of occasional concern have been the collapse of crop canopies throughout the season following heavy rainfall which causes stem failure. It is anticipated that this may cause harvesting problems and contribute to loss of yield.

The low radiation use efficiencies reported here indicate a number of areas where further research/ crop breeding effort is required in order to increase yield, particularly increased tolerance of low temperatures, higher tolerance of drought or higher water use efficiency. Experimental material grown in UK and Europe is of unimproved genetic origin, principally of the two species examined in this project. A considerable diversity of genetic material is held at the National Collection at ADAS Arthur Rickwood, and this has been the subject of detailed taxonomic study (Hodkinson, Renvoize & Chase, 1997). It is anticipated that the current limitations to yield in *M. x giganteus* and *M. sacchariflorus* could be overcome with an evaluation of wild source material for low temperature and drought tolerance and a plant breeding programme using material from the collection.

During the life-time of this project we have gained a reasonable understanding of the husbandry and growth characteristics of a completely new crop to UK agriculture. We have seen that yields averaging 18 odt ha^{-1} are achievable on a wide range of soils, even under conditions of extreme moisture stress. Crops established during dry years and/or in climates and soils that are not optimal for yield expression will take longer to establish and may suffer a long-term yield penalty. Perennial crop such as Miscanthus may exert a ‘memory’ effect on crop growth characteristics such that the influence of one season, during which assimilates are laid down, is carried forward to the following season. Thus a period of drought may retard the growth of plants for many seasons afterwards.

Objective 4 - to identify economics, market opportunities, prices and export opportunities for Miscanthus products.

A desk study/review was undertaken to determine the detailed production economics and market options for miscanthus. This report has been submitted to MAFF and is found at Annex 3. The review had the following specific objectives:

1. To provide a comprehensive analysis of costs of production of Miscanthus.
2. To identify and evaluate the full range of markets into which Miscanthus might enter as a viable crop.
3. To compare the likely commodity price of Miscanthus in a range of markets.
4. To provide an appraisal of likely market size and value and assess the opportunity for import substitution.
5. To identify niche cropping opportunities, with particular respect to land types and waste deposition.
6. To assess the comparative position of Miscanthus by reference to UK average gross margins for selected examples of cereals and break crops.

The likely costs of all aspects of Miscanthus production including transport costs to the factory were calculated (Tables 8-10 and Annex 3), and from this information the break-even costs of production for the entire crop lifetime (set at 19 years) were calculated. Two harvesting options were considered (cutting & baling or direct chopping), both of which had been demonstrated as feasible at ADAS technology transfer days held at ADAS Arthur Rickwood.

Table 8. Cost of establishing one hectare of Miscanthus

Activity	Cost (£ ha^{-1})
rhizome costs (@ 20,000 plants/ha)	1000
Cultivation	76
Fertiliser	48
Herbicides	80
Contract planting	116
Insecticides/fungicides	0
Total	1320

Table 9. Annual husbandry costs for one hectare of Miscanthus

Activity	Cost (£)
Cultivation	0
Fertiliser	37
Herbicides	32
Fencing	0
Insecticides/fungicides	0
Total	69

Table 10. Cost of harvesting one hectare of Miscanthus, assuming 30t of fresh biomass standing, and subsequently storing for 6 months.

Activity	Cost (£ ha^{-1})
Cut & bale Contract cutting, baling, carting & stacking	169
Storage costs	34
Total	203
Direct chop	
Contract forage harvesting, carting and stacking	125
Storage costs	86
Total	211

The break-even cost for baled Miscanthus was calculated to be £46 in the absence of any support, and that of chipped Miscanthus to be £53. At these costs Miscanthus could not be grown commercially. However, Miscanthus is currently supported (it is eligible for set-aside payments), and will compete against alternative enterprises that are also supported. Inclusion of current set-aside payments reduces the cost of production to £22 odt^{-1} and £26 odt^{-1}, for baled and chipped Miscanthus, respectively.

Miscanthus production costs were insensitive to variation in yield or crop moisture content. Doubling yield decreased the break-even cost requirement to £20 odt^{-1}. This insensitivity is because the unit costs of harvesting and storage, which are linked to yield, are high. Indeed, reducing harvesting costs is the most rapid way of reducing production costs; a reduction in baling costs from £5 to £3 per bale will reduce the break-even cost by £9 odt^{-1}. The other characters measured (crop longevity and propagule cost) do exert a significant effect on commodity price. In the absence of support payments, yield does become the most important determinant of break-even price.

The economic feasibility of Miscanthus as a feedstock for the energy, composite materials, paper, animal bedding and waste minimisation industries was investigated. The foremost market for Miscanthus was found to be for electricity generation, for which the baled product will be appropriate. In this market, it is anticipated that an ex-farm price of £40 odt^{-1} is attainable. If totally unsupported, miscanthus net margins (as with coppice) are negative and miscanthus is not a viable option for the farmer. With the inclusion of set-aside support (pegged at Agenda 2000 levels; £252 ha^{-1} yr^{-1}), neither miscanthus or coppice are viable. The provision of an additional establishment payment, similar in magnitude to that currently available for coppice (i.e. £1,000 ha^{-1}), is required in order to make miscanthus an economically viable energy crop (net margin of £286 ha^{-1} yr^{-1} compared with £255 for coppice). The requirement for such high levels of support indicate the importance of further R&D directed towards reducing establishment costs and increasing yields and harvesting efficiency.

The alternative markets, notably paper pulp, medium density fibreboard production and animal bedding are more speculative. Pulp and medium density fibreboard (MDF) markets could offer very good or very poor returns due to the volatility of world market prices. Also, the processing capacity of existing plants in the UK is huge, they are unwieldy and the conservatism of the producer makes it unlikely that a shift from wood based products to Miscanthus would take place. Also, they are located in remote parts of the UK and consequently transport distances would be prohibitively expensive. However, more local initiatives are beginning to appear and might offer long term (say 10 years hence) opportunity. The animal bedding market is purely speculative. Insufficient evidence of the value of Miscanthus exists. However, if appropriate, margins to the farmer could be very attractive.

CONCLUSIONS

Biological implication of this work

From the work reported here it appears that the crop meets many of the criteria for an ideal energy crop because:

1. where moisture or frost damage does not limit radiation use efficiency, high biomass yields are attainable due to the long duration of complete canopy cover;
2. the crop can successfully overwinter in the UK;
3. preliminary evidence indicates a stable yield profile in the ‘mature’ phase
4. the crop demonstrates efficient use of nutrients;
5. the crop has high resistance to pests, diseases or grazing mammals;
6. ease of husbandry and handling at all stages, makes it acceptable to farmers.

However, certain concerns are still apparent with this crop, in particular:

1. unproven field-scale establishment systems;
2. insufficient cold tolerance to withstand springtime frosts which destroy the crop canopy;
3. insufficient evidence of long-term yield profile;
4. high moisture content at harvest (30-70%);
5. a significant component of yield lost through leaf fall in most seasons;
6. poorly developed markets.

This work has demonstrated that the husbandry of miscanthus is straightforward and that fertiliser application on some soils will be unnecessary, and on all should be low. Following this, stem extension and leaf production are rapid, such that crop heights may attain 2m in the first season and in excess of 3m in the second and subsequent seasons. *M. sacchariflorus* appears to be approximately 50cm taller than *M. x giganteus*. Stem dynamics of the two species appear similar; as many as 150 stems are produced initially, but as the crop grows and the canopy begins to shade lower areas, so this initial stem density declines rapidly to an equilibrium density of 60-80 stems m^{-2}.

The predominant difference between initial plant populations is the time taken to achieve this stem spatial arrangement, and the leaf area index attained, which in turn is related to the orientation of the leaves. We have shown that miscanthus yield is related to the annual accumulated temperature above a base of 6°C (the threshold for leaf expansion). This needs further elaboration and verification. An average of 70% of mid summer yield is harvested in winter, the remainder being lost as leaf litter, and the nutrient content of the standing crop at harvest is low in N and P. Options for increasing yield recovery during harvest, by looking at November rather than March harvest should be addressed.

Even though relatively low RUE's are reported, above-ground biomass accumulation for both *M. x giganteus* and *M. sacchariflorus* exceeded 20 odt ha^{-1} in many years – considerably higher yields than attained with the main alternative biomass crops. During the initial 2-4 years, it appears that the yield penalty observed at lower densities is due to less efficient canopy architecture and lower canopy duration rather than decreased RUE. It is clear that the year of establishment is crucial to miscanthus yield, and that in ideal conditions the optimal yield may be attained in the second season. Overall, miscanthus must be considered a crop with high potential.

Policy implications of this research

This project supported the policy objective of diversifying the biomass cropping base in order to achieve a significant contribution from energy crops to UK energy demands by 2010. The work has demonstrated that this annually harvested species is capable of higher yields than those projected for coppice, and that as such the amount of land required to produce a given quantity of biomass will be lower. This will require a lower supply radius to the power station to be used. The work has demonstrated that the environmental impact (in terms of fertiliser and agrochemical input) of growing high yields of miscanthus are low, thus meeting policy sustainability requirements.

The work on predicting miscanthus costs of production indicates that policy makers will need to consider the provision of planting grants in addition to set aside payments if current interest in the crop is to be translated into commercial ventures. However, the amount required to stimulate planting is no more than that required for short rotation coppice. In the short to medium term the only realistic use is for energy and alternative enterprises will not make economic use of miscanthus feedstock. Miscanthus will be used as an energy crop in tandem with other sources like straw, forestry residues and possibly coppice, rather than as an exclusive feedstock. The next phase of Miscanthus production has already begun with the establishment of a 10 ha field crop in an association between EPR Ely (the developers of the Ely straw-burning power station) and ADAS. The continuation of the small scale studies reported here, through project NF0407, will allow yield profile and crop longevity to be monitored into the second decade of production – a unique insight into the performance of this perennial energy grass. Whilst the genetic resource for commercial production is limited to two 'varieties', large scale cropping should be discouraged, both because a limited genetic base increases susceptibility to large-scale crop failure and also because the first cycles of breeding should result in far higher yielding crops.

REFERENCES:

- Anon. (1991). Non-food uses of agricultural products. House of Lords Paper 26, Select Committee on the European Communities, 7th Report, Session 1990-91. London: HMSO, 219pp.
- Beale C V & Long, S P (1995). Can perennial C4 grasses attain high efficiencies of radiant energy conversion in cool climates? Plant, Cell and Environment, 18, 641-650.
- Bullard, M. J., Heath, M. C. and Nixon, P. M. I. (1995) Shoot growth, radiation interception and dry matter production and partitioning in Miscanthus sinensis 'Giganteus' grown at two densities in the UK during the establishment phase. Annals of Applied Biology, 126, 365-378.
- Bullard, M.J., Nixon, P.M.I., Kilpatrick, J.B., Heath, M.H. & Speller, C.S. (1995). Principles of weed control in Miscanthus spp. under contrasting field conditions. British Crop Protection Council - Weeds, Brighton Conference, November 1995.
- Christian, D.G., Poulton, P.R., Richie A. B. & Yates N.E. (1997). The recovery of ^{15}N-labelled fertiliser applied to Miscanthus x giganteus. Biomass and Bioenergy, 12, 21-24.
- DTI (1999) New and Renewable Energy: Prospects for the 21st Century. London:HMSO
- Heath M C, Bullard M J, Kilpatrick J B & Speller C S (1994) A comparison of the production and economics of biomass crops for use in agriculture or set-aside land. Aspect of Applied Biology 40, Arable Farming under CAP reform.505-515
- Hodkinson, TR; Renvoize SA & Chase MW (1997). Sytematics of Miscanthus. Aspects of Applied Biology 49, Biomass & Energy Crops, 189-198.
- Lewandowsi I & Kicherer, A. (1997). Combustion quality of biomass:practical relevance and experiments to modify the biomass quality of Miscanthus x giganteus. European Journal of Agronomy, 6, 163-177.
- Matamura M and Yukimura T (1975). Fundamental studies on artificial propagation by seeding useful wild grasses in Japan. VI. Germination behaviour of three native species of genus Miscanthus. Res. Bull. Fac. Agr. Gifu Univ. 38, 339-349.
- Nixon, PMI (1997). Does the common rustic moth Mesapamea secalis (L.) represent an economic threat to Miscanthus? . In: (Bullard M J, Ellis R G, Heath M C, Knight J D, Lainsbury M A, Parker S R eds) Aspects of Applied Biology 49, Biomass & Energy Crops, 137-143.
- Osada T (1993). Illustrated grasses of Japan (enlarged edition). Tokyo:Heibonsha Ltd.
- Rutherford I & Heath M C(eds) (1992). The Potential of Miscanthus as a Fuel Crop. ETSU B 1354. Harwell:ETSU 125pp.
- Schwarz, K-U, Murphy D P L,& Schnug E (1994). Studies of growth and yield of Miscanthus x giganteus in Germany. Aspect of Applied Biology 40, Arable Farming under CAP reform. 533-540.
- Walsh M ed.(1997). Miscanthus Handbook. Contract FAIR 3-CT96-1707. Brussels: European Commission. 178 pp.