DEPARTMENT for ENVIRONMENT, FOOD and RURAL AFFAIRS **CSG 15**

Research and Development

Final Project Report

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Project title	Continued assessment of agronomy and yield potential of Miscanthus for industrial cropping in the UK
DEFRA project code	**NF0405**
Contractor organisation and location	ADAS ADAS Arthur Rickwood Mepal, Ely Cambs. CB6 2BA
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Executive summary (maximum 2 sides A4)

Miscanthus is an energy crop; a perennial rhizomatous grass that has been introduced to UK agriculture in the last fifteen years and which is now being grown for both energy and fibre uses. The purpose of this study was to extend our knowledge of miscanthus yield, and thus economic viability, in the post-establishment phase of the crop and to develop, from field measurements and literature, a parameterised crop yield model that would be of use to planners and farmers under current and future climate scenarios. The objectives of this study were:

- To determine the yield profile of miscanthus growing at two densities at seven sites in England, in their post-establishment phase.
- To identify, and where appropriate quantify, yield loss inducing factors (pests, lodging, and stem basal diseases).
- To identify key environmental variables and their effect on crop growth and development based on previously determined measures of physiological efficiency.
- To maintain the national miscanthus collection.
- To revise the economic model for miscanthus based on additional growth and yield data.
- To develop and parameterise a simple model of miscanthus yield.
- To analyse the sensitivity of the model used in predicting the yield of miscanthus.
- To use the model to assess the spatial and temporal variability of yields across England and Wales.
- To predict the yield of *M. x giganteus* given UK climate change scenarios by the sub-objectives:
- To model the yield of miscanthus across England and Wales (5 x 5 km units) under UK climate change scenarios and review the weather generator used to derive daily weather for these scenarios.
- To qualitatively consider other factors that affect yield.

The field trials under investigation were established under a previous Defra project (NF0403) in either 1992 (ADAS Arthur Rickwood, ADAS Rosemaund and Buckfast Abbey) or 1994 (ADAS sites at Bridgets, Boxworth, Gleadthorpe and High Mowthorpe). The yield (oven dry tonne; odt) results from the previous study (NF0403) were included in the analyses presented to provide long-term yield profiles. Key results were that the yield profile of miscanthus, irrespective of site, can be divided into two phases; a yield-building phase between 2-5 years in duration (depending on site suitability and climate) followed by a yield plateau phase. In the plateau phase the mean yield of the Original sites (planted in 1992) was 19.9 odt ha^{-1} yr^{-1}. Those sites planted in 1994 (New sites) could be distinguished by yield expression; yields at high productivity sites (Boxworth and Bridgets) where mean yield was 17.8 odt ha^{-1} yr^{-1} compared with sites suffering moisture stress (Gleadthorpe) or exposure and high latitude (High Mowthorpe) where mean yield was only 12.3 odt ha^{-1} yr^{-1}.

For the Original sites, distinct differences in yields between the two crop densities were evident for the first four years; in subsequent harvests, yields were similar for the two densities. This trend was replicated at the New sites, although a longer yield-building phase of five years was seen. The yield profiles indicated that, on the experimental sites investigated, the additional yields achieved in the first 3-5 years of cropping did not justify the additional propagule cost of increased planting density from 10,000 rhizomes ha^{-2} to 40,000 rhizomes ha^{-2}. However, at a practical level the planting rate must consider commercial establishment rates, and weed control issues. In addition, poorer quality sites than those used here will, generally, be cropped, and these can be expected to have an even longer yield-building phase. Consequently, a planting density of 20,000 rhizomes ha^{-2} should be used.

This project has confirmed the ease of husbandry and yield potential of miscanthus. No significant disease, pest or lodging problems have been detected. The plots are a unique resource to monitor the long-term yield profiles of this new crop.

The data collected at the seven research sites were used to parameterise a simple model of potential yield. The model was based on resource capture (Monteith, 1977). The model was further developed to predict yield in water limited circumstances by inclusion of a drought reduction factor. Modelled yields, both potential and water-limited, provided a good estimation of measured yields at the Original sites; an average 5% difference between the potential and measured yield at Buckfast Abbey with smaller differences at the other two sites. Using a drought reduction factor, the modelled yield predictions were notably improved at High Mowthorpe, Bridgets, and Gleadthorpe and at Arthur Rickwood during 1995 when the effect of drought was observed. The modelling exercise indicated that the duration of the yield-building phase was likely to be related to limited water availability in the establishment years. Sensitivity analysis of the model identified rooting depth and soil water availability as critical factors in estimating yield under drought conditions.

The model was applied to 5 x 5 km cells across England and Wales to produce miscanthus productivity maps. The potential impact of climate change on yield was modelled using scenarios for the 30 year period centred on 2020 (Medium-High) and 2050 (Medium-High) of UKCIP (UK Climate Impact Programme). These scenarios forecast drier summers with rainfall less evenly distributed throughout the year. The mean modelled yield output centred on 2020 and 2050 predicted, on average, good yields for many areas of England and Wales with deep moisture retentive soils despite the drier summers. Sites with shallow, light soils were increasingly affected by water limitation. For a long-term perennial crop, such as miscanthus, careful site selection is essential. The key for this modelled prediction lies in the earlier emergence of the crop. Warmer spring temperatures, fewer late frosts and increased winter rainfall, allowed the modelled crop to develop quickly in late spring. For the future climate scenarios, rapid canopy development occurred earlier in June when water was still available in the modelled soil profile. When the dry period in August occurred, within the model, the crop had in many instances already reached canopy closure. Early senescence of the crop in the dry late summer months may enable autumn harvesting. The main outcome of this climate change modelling work was to indicate that the majority of sites that would presently produce acceptable yields of miscanthus would continue to do so in the future. The most vulnerable soils to crop failure or poor yield were those where moisture supply is already limiting. Generally, greater variation in yield between seasons would be seen at any site.

A market analysis was undertaken and the cost of miscanthus production examined. To compare the competitiveness of miscanthus in the various markets examined, the breakeven cost (BEC) was calculated as the Net Present Value, discounted at 8% for 19 years, of producing one oven dried tonne (odt) of miscanthus in the absence of any support. The breakeven cost of production of one odt of baled miscanthus, the most likely format for energy, was £33.75 ex-farm. The breakeven cost of production of one odt of chipped and dried miscanthus, suitable for animal bedding, was £55.25 ex-farm, and one odt chipped and delivered without drying was £51.09, suitable for pulp fibre production (and speculative markets such as bio-plastics, construction materials, plant growth media). Miscanthus planted for energy can receive the Energy Crop Scheme planting grant (£920 ha^{-1}). Including this planting grant in the determination of breakeven costs reduced the price of one odt of baled miscanthus to £26.49.

Sensitivity analysis on the cost of producing one odt of baled miscanthus revealed that the most cost-sensitive elements of miscanthus production were the inter-linked components of yield and harvesting costs. The persistence of the crop also had an effect; reducing the life of the crop to 15 years resulted in an increased BEC to £35.75 odt^{-1}. These sensitivies can be linked to the impact on yield predicted by the climate change scenarios. Areas that currently provide adequate yields but have been predicted to display large yield variability in reponse to climate change should be avoided.

Miscanthus can be grown for energy markets on set-aside land or on non set-aside land, with additional support coming from the Energy Crop Scheme establishment grant. A €45 ha^{-1} yr^{-1} EU incentive is available for miscanthus grown on non-set-aside land. The various support systems were applied to growing miscanthus for energy as a farm enterprise with product value set at £26 odt^{-1} in order to determine profitability. While all three scenarios provide positive gross margins, the only scenario to achieve a positive net margin was with the ECS planting grant and set-aside payments factored in. With no support a minimum product value of £46 odt^{-1} was required to achieve a positive net margin. If grown on non set-aside land and claiming the €45 ha^{-1} $year^{-1}$ EU incentive a product value of £38 odt^{-1} is required for a positive net margin. A general fixed cost of £308 was used to determine these margins and varying the fixed cost value used will, of course, change the profitability. Also, economies of scale are not captured when margins are determined on a hectare basis. The suitability of a miscanthus operation to a specific holding must, of course, be determined on a case by case basis.

Outside the energy market, animal bedding is the most developed market. In general, a large market for animal bedding exists and the cost of bedding products varies from £10 – 350 $tonne^{-1}$ depending on the specific target market. The market value of miscanthus bedding will reflect its quality as a bedding material, which has yet to be fully appraised and accepted. Thus, depending on the quality of the product, miscanthus bedding could be prohibitively expensive to produce, or an extremely lucrative farm enterprise. If miscanthus was established as a suitable bedding material and a product value of £80 odt^{-1} applied it would provide a significant market for this crop with increased returns for the grower; potentially £465 ha^{-1} annual equivalent gross margin (or £309 ha^{-1} net margin).

In summary, this project continued to monitor the agronomic performance of miscanthus (*Miscanthus x giganteus*) plots; extended the long-term yield profiles of miscanthus growing at two densities; measured resource capture at three of the sites; used resource capture data and published literature to construct a potential yield model for miscanthus; further developed the model to predict water-limited yield; tested the sensitivity of the model; the resultant model was used to develop national potential yield and water-limited yield maps using GIS; the model was used to develop national potential yield and water-limited yield maps using future climate change scenarios; other factors thought to effect yield potential were identified and discussed; an economics and market analysis of miscanthus was undertaken. Defra's policy objective in bioenergy is to provide basic knowledge to aid the development of energy crops. This study has continued to do this by demonstrating yield capability of miscanthus and more recently by producing refined yield models and yield maps. The agronomic understanding underpinning this study has fed through to a range of other studies and enabled industry to begin to use the crop commercially. By demonstrating yield with minimal inputs, the work has underpinned Defra's objective of supporting crops that protect the environment at reduced chemical and energy inputs.

Scientific report (maximum 20 sides A4)

Background and objectives

The UK government has signed up to a 12% reduction in GHG emissions by 2010, including a 20% cut in CO_2 emissions. Within the Kyoto Climate Change Agreement, the UK is committed to a 12.5 % reduction in GHG emissions by 2008-2012. Under this agreement, 10% of the UK's primary energy will be generated from renewables by 2010. The recent Energy White Paper (DTI, 2003) adopts the aspirational target of a 60% reduction by 2050. At present, there is a 7% deficit between current renewable electricity generation and the 2010 target. The proportion of renewable electricity grew from 2.6% to 3.0% from 2001 to 2002. Energy crops do not contribute to increased atmospheric CO_2 levels as the carbon released during use is taken up from the atmosphere during the growing season. The UK government identifies biomass-derived energy (thermo-chemical conversion of bio-residues and/or energy crops) as one of the main routes by which it can achieve its obligations under the Kyoto Climate Change Agreement (DTI, 2001). Perennial energy crops also have the capacity to act as short-term carbon sinks as carbon is sequestered in the soil for the 15-20 year life time of the crop (Bauen, 2001).

Miscanthus is a genus of perennial sub-tropical grasses, combining high biomass yields with low input requirements and an annual harvest cycle. Rhizomes (or tissue-cultured plants) are planted during late April and May. Each spring, multiple shoots appear once daytime temperatures exceed approximately 6°C. Growth is extremely rapid, producing cane like stems which may reach 2-3m in height. Once full light interception is achieved, the lower layers of leaves begin to senesce, whilst shoot growth continues into 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. The crop is not harvested in the year of establishment but in subsequent years is harvested in February or March. 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, when an accumulated temperature of 200-400°C has been reached. Thus, an annual cycle of biomass harvest is achieved with this crop.

The high yield potential of miscanthus has been confirmed in a number of field-scale trials funded or co-funded by Defra (Christian *et al*., 1997: Bullard & Kilpatrick, 1997; Bullard & Nixon, 1999) which have indicated that harvestable yields of at least 15 odt ha^{-1} yr^{-1} were attainable by the fourth season of growth. A previous study (NF0403) investigated miscanthus biomass yields and its suitability for UK cropping at seven sites. That study reported that miscanthus had high potential as a biomass crop requiring low inputs. The results could not distinguish if the lower yields at less than optimal sites were a result of a prolonged yield-building phase or of long-term lower yield potential. The present study continued the evaluation of miscanthus at these seven sites so that long-term yield profiles could be determined.

To enable miscanthus uptake to be successful and widespread, miscanthus must compete in the market place and provide an income for the grower. A market analysis was undertaken and an economic analysis to determine product price and competitiveness was also conducted. This updated the previous analysis undertaken in 1999 (NF0403) and is presented in Annex 1.

There was a need not only to provide an indication of likely yield but also to quantify the variability in these predictions across England and Wales for both current and future climate scenarios. Miscanthus can have a cropping lifetime of at least 15 years, and indications of variations in yield under predicted climate change are therefore important when considering the economics of maintaining a crop over such a long period. The combination of higher temperatures and changed precipitation regimes has implications for water balances, nutrient requirements and loss, and the organic content of soils, with additional consequences for irrigation demand and usage (Bisgrove & Hadley, 2002). In order to ascertain the full economic potential of this crop, there was a need to translate information collected at a limited number of field sites into a model that can predict yields across England and Wales. To achieve this, data collected at seven research sites were used to parameterise a simple model of potential yield and yield given water limitation, which has been incorporated into a GIS framework to map the estimated yields of miscanthus across England and Wales for both current and future climate scenarios. In addition to the results presented here, a series of maps using the miscanthus yield model are presented in Annex 2.

The objectives of this study were:

1. To determine the yield profile of miscanthus growing at two densities at seven sites in England, in their post-establishment phase.

2. To identify and where appropriate quantify yield loss inducing factors (pests, lodging, and stem basal diseases).

3. To identify key environmental variables and their effect on crop growth and development based on previously determined measures of physiological efficiency.

4. To maintain the national miscanthus collection.

5. To revise the economic model for miscanthus based on additional growth and yield data.

Additional objectives agreed as the project progressed. These were:

6. To develop and parameterise a simple model of miscanthus yield
   To analyse the sensitivity of the model used in predicting the yield of miscanthus.

7. To predict the yield of *M. x giganteus* given UK climate change scenarios by the sub-objectives:
8. To model the yield of miscanthus across England and Wales (5 x 5 km units) under UK climate change scenarios and review the weather generator used to derive daily weather for these scenarios;
   To qualitatively consider other factors that affect yield.

Materials and methods

The study involved continued investigation of miscanthus biomass yield profiles at seven sites. The miscanthus species investigated was originally identified as *M. sacchariflorus* but has since been reclassified as *Miscanthus x giganteus* Greef et Deuter ex Hodkinson & Renvoize (Hodkinson & Renvoize, 2001). The plots were established in the project NF0403 and all sites had identical (10m x 10m) experimental plots in place; two initial plant densities (1 and 4 plants m^{-2}), replicated 5 times. However, the sites varied in the year they were established and the predicted productivity of the sites. Therefore, for biomass yield profiles, the sites were grouped by age and yield class (Table 1). Field data from these sites were collected to support objectives 1, 2, 3, 6 and 7.

Field assessments (Objectives 1 –3)

Crop growth at each site was monitored throughout the four growing seasons. The date of shoot emergence and the date when 50% of the plants had an unfurled leaf were recorded to determine the start of the growing season and the rate of early growth during low spring temperatures. Biomass accumulation throughout the growing season was monitored by monthly assessments of crop height and stem number $area^{-1}$. Additional weekly measurements of radiation interception (using tube solarimeters) and non-destructive canopy area were made at three sites (Arthur Rickwood, Boxworth and High Mowthorpe). Daily meteorological measurements of air and soil temperatures, rainfall and accumulated solar radiation were recorded.

Table 1. Details of site and predicted productivity potential used to group seven miscanthus sites

Grouping & site	Established	County	Altitude (m)	Mean Annual Rainfall (1994-2000) (mm)	Predicted productivity potential
Original	1992				
Rickwood		Cambridgeshire	-3	648	High potential
Buckfast Abbey		Devon	50	838	High potential
Rosemaund		Herefordshire	84	687	High potential
New, high potential	1994				
Boxworth		Cambridgeshire	58	559	Limited by high pH and water logging
Bridgets		Hampshire	91	709	Limited by high pH
New, low potential	1994				
Gleadthorpe		Nottinghamshire	60	638	Limited by moisture supply
High Mowthorpe		N. Yorkshire	195	742	Limited by temperature, exposure and high pH

Potential yield loss inducing factors (frost damage, lodging and pest and disease damage) were also assessed. From July onwards, the crop was surveyed at regular intervals for presence of lodging and the presence of stem basal diseases. From March until June, the crop was inspected for evidence of common rustic moth activity (shoot die back, larval exit holes on the side of the affected stem).

The plots were harvested in February or March each year and biomass yield, moisture content and nutrient content (N, P and K) of the harvested material was assessed.

Maintaining the Miscanthus genebank (Objective 4)

The Miscanthus genebank held at Arthur Rickwood was maintained to a high standard. Maintenance of the genebank included control of spreading rhizomes to ensure distinction of the individual accessions, annual cutting and general maintenance such as regular weed control. New accessions received from RBG Kew were set out in the genebank as soon as practicable in each season.

Revision of the economic model for miscanthus (Objective 5)

An update of the analysis of the production economics and market assessment for miscanthus undertaken in 1999 (NF0403) was conducted. Where possible, the hypothetical costs and product values used previously were replaced with current actual costs. The analysis determined breakeven costs (odt^{-1}) for various miscanthus production scenarios. Net margins and gross margins were presented as annual average, net present value (NPV) and annualised equivalent value (AEV). Potential markets for miscanthus were also reassessed in terms of development, scale and product price.

The break-even cost (P) was calculated as:

$$P = \frac{\sum_{t=1}^{T} \frac{C}{(1+d)^t}}{\sum_{t=1}^{T} \frac{Y}{(1+d)^t}} \qquad (1)$$

Net present value was calculated as:

$$\Sigma((P.Y)-C).(1/(1+d)^t) \qquad (2)$$

Where, T = duration of productive crop, t = sequential year of crop, Y = yield, d = discounted rate (set at 8% p.a.) and C = costs.

Development of a model of miscanthus yield and assessment of the spatial and temporal variability of yields across England and Wales (Objective 6)

In the first instance, the objective was to develop a model of 'potential' yield. Details of the modelled sites are presented in Table 2. A data-driven approach was used to parameterise a simple empirical productivity model (Monteith, 1977). Measurements of the crop morphology, emergence dates, crop nutrient off-take and experimental yields of miscanthus recorded each season since 1992 at the seven trials, as well as measures of light interception and crop canopy development from ADAS Arthur Rickwood, ADAS Boxworth and ADAS High Mowthorpe, were used in the model parameterisation. The model was driven essentially by cumulative temperature and incident radiation, and was not formulated to reflect limiting responses to environmental factors such as pH stress, exposure and nutrient deficiency.

It has been reported (Clifton-Brown & Lewandowski, 2000) that for many locations, water availability is a significant environmental factor that may restrict miscanthus from reaching its potential yield. Therefore, in addition to the model of potential yield, an additional objective that estimated yields given water limitation was undertaken. The model of potential yield and water-limited yield was validated against data collected at the 7 trial sites. Both models were applied annually from the year of establishment although the models assumed that the miscanthus was past the yield-building phase i.e. crop age over 2 years. In addition, the models were applied within a GIS framework to estimate yields across England and Wales driven by weather data and soil information for 5 x 5 km grid cells.

Table 2. Mean duration of the growing season and mean incident solar radiation during growing season at the seven sites used to i) provide data for the development of a miscanthus productivity model and ii) to analyse the sensitivity of the model.

Site	Average duration of growing season (1994-2000) (days)	Mean incident solar radiation during growing season (1994-2000) ($MJ\ m^{-2}$)
ADAS Arthur Rickwood	186	2703
Buckfast Abbey	223	2916
ADAS Rosemaund	175	2581
ADAS Boxworth	193	2757
ADAS Bridgets	178	2748
ADAS Gleadthorpe	174	2461
ADAS High Mowthorpe	183	2519

Potential yield model

To estimate the potential yield of miscanthus, the following productivity equation for potential yield, adapted from Beale and Long (1995), and based on the principles developed by Monteith (1977), was applied (Equation 3). The equation was applied on a daily basis for the length of the growing season, and the cumulative yield was calculated at the end of the growing season

$$Y_{P(k)} = \sum_{k=1}^{n} S_{t(k)} \varepsilon_{i(k)} \varepsilon_c \, d_{f(k)} \qquad (3)$$

Where, (Y_p) is the total above-ground dry matter yield at final harvest ($g\ m^{-2}$). The argument (k) denotes the value of the associated variable on the kth day during the growing season; S_t is the daily incident solar radiation over the growing season ($MJ\ m^{-2}$ PAR); ε_i is the efficiency with which the crop intercepts that radiation (dimensionless); ε_c is the efficiency with which the intercepted radiation is converted into above-ground biomass (g d.m. MJ^{-1} PAR intercepted); d_f is the drought reduction factor (dimensionless) and n is the length of the growing season. For potential yield d_f is unity.

Parameterising the yield model

Application of the model to each of the trial sites was driven by daily rainfall, maximum and minimum daily air temperatures and sunshine hours for stations closest to or at each research site. Sunshine hours were converted to solar radiation in MJ m^{-2} (Allen *et al*. 1994).

Length of growing season (n)

New shoots of miscanthus are sensitive to late frosts (Bullard & Nixon, 1999) and, therefore, in this model application, the start of the growing season was taken as the first day after which the daily minimum air temperature for each site did not fall below zero degrees Celsius. The end of the growing season was identified as the last day before a minimum air temperature of below zero degrees Celsius was recorded. The modelled season typically started in April-May and ended in late September, which was in good agreement with dates of shoot emergence reported at the experimental sites. Mean values are presented in Table 2

Crop radiation interception (ε_i)

Observed data on incident radiation and canopy interception measured for the growing seasons 1998-2000 at Boxworth, Arthur Rickwood and High Mowthorpe, mean values presented in Table 2, were used to calculate leaf areas at regular intervals by rearrangement of the Monsi-Saeki equation (Monsi & Saeki, 1953) and assuming a radiation extinction coefficient of -0.47.

$$\varepsilon_{i(k)} = 1 - e^{-K*LAI_{(k)}} \qquad (4)$$

ε_i is the efficiency of canopy interception of radiation; LAI is the Leaf Area Index and K is the radiation extinction coefficient.

The relationship between calculated Leaf Area Index (LAI) and degree-days above 6 ^{o}C (DD6), (6 ^{o}C being the base temperature for leaf expansion (Clifton-Brown & Jones, 1999)), was approximated as a linear regression from the start of the growing season until LAI reaches a value of 6: *LAI = X*DD6*. This relationship assumes that an effective crop canopy is achieved for a maximum LAI of 6. For data collected at Boxworth, the coefficient (*X*) varied in the range 0.0071 to 0.0093. A mean value of 0.0085 was used for all sites, in combination with equation 4 to calculate intercepted radiation ε_i and biomass gain in the daily simulations.

Radiation use efficiency (ε_c)

The parameter ε_c equates to Radiation Use Efficiency (RUE) i.e. unit of biomass produced per unit of solar radiation intercepted by crop canopy per area (g MJ^{-1} PAR m^{-2}). The annual RUEs calculated for miscanthus grown from 1994-1998 at ADAS Arthur Rickwood (Bullard & Nixon, 1999) were used to calculate a mean RUE of 1.91 g MJ^{-1} PAR m^{-2}, for above ground biomass. This RUE covered the entire growing season.

Drought factor (d_f)

The threshold drought reduction factor d_f was estimated as the ratio of actual evapotranspiration (AET) to potential evapotranspiration (PET) for miscanthus. The value of d_f varied between zero and unity and was set to unity (non-limiting) for modelled potential yield. In the application of the water limited model d_f was calculated on a daily time-step at each site, and gave an estimate of the above ground dry matter yield, accumulated over the growing season (Price *et al.,* 2004). The calculation of AET and PET are described below.

Daily potential evapotranspiration (PET) was calculated using the equations presented in Allen *et al.* (1994) and assumed that the maximum crop height was 2.5 m. Rainfall interception was estimated using the relationship for miscanthus reported in Riche and Christian (2001). Actual evapotranspiration (AET) as a function of PET was calculated using the method of Bailey and Spackman (1996) from the ADAS IRRIGUIDE model for irrigation planning. To calculate AET, estimated values for the available water capacity (AWC) of the soil at each site were required. These values, presented in Table 3, were derived from data in the National

Soils Research Institute (NSRI), Cranfield University, SEISMIC soil series database (Hallet *et al*. 1994). Neukirchen *et al.* (1999) reported that in field trials of miscanthus, the topsoil (0-30 cm) contained 28% of the root's biomass with the number of roots decreasing down to a depth of up to 2.5 m. For the application of the Bailey and Spackman method, it was assumed that the total available water was the sum of the water held between field capacity and a tension of 2 bars to a total depth of 150 cm (a maximum rooting depth for miscanthus of 1.5 m assumed), and water held between a tension of 2 and 15 bars available to the plant to a depth of 30 cm. In addition, Jarvis *et al.* (1984) suggest that crops are able to extract more water than is available in shallow calcareous soils alone, thus negating the effects of droughtiness. Chalk can hold readily available water to plants amounting to 15-35 percent of its volume (Bunting & Elston, 1966). Therefore, for ADAS Bridgets, the AWC was revised to 190 mm to reflect additional water capacity available from fissures in the underlying rock.

Following further model validation, the function was modified such that d_f =1 when sufficient water is available for the model to grow at the potential yield and below this critical threshold, d_f was a function of the water remaining in the profile. Each year, on day one of the growing season, the soil moisture deficit (smd) for the 1.5 m deep soil profile, as defined for the Miscanthus crop, was set to zero. Water remaining in the profile was calculated each day as (1- (smd/total awc)). On each day thereafter, the soil moisture deficit was calculated as defined below.

$$SMD_{(t)} = SMD_{(t-1)} + AET_{(t)} - ERain_{(t)} \qquad (5)$$

where SMD is the soil moisture deficit; AET is actual evapotranspiration (mm) and $ERain$ is effective rainfall (mm) and the argument (*t*) denotes the value of the associated variable on the *t* th day during the growing season.

The difference between the modelled and measured yields over the growing seasons was reduced by varying the critical factor in the range 0-1 to determine one critical threshold of water remaining that was applicable to all the years for all 7 trial sites. A critical threshold of water remaining in the profile of 0.2 was identified below which d_f =2*(water remaining). For the days when the water remaining in the soil profile was lower than this threshold, yield increments were less than the potential. In addition, a critical wilting point, when the water remaining was 0.05, was added. When the water remaining in the profile had reached this point, the crop was considered to have reached a critical wilting point, d_f = 0 and therefore no further biomass was incremented for the remainder of the growing season. The value of d_f was then applied in equation 1 to estimate the dry matter yield.

Table 3. Mean values for annual rainfall, soil available water capacity, growing season duration and incident solar radiation

Site	Mean rainfall during model growing season (1994-2000) (mm)	AWC Estimates of available water capacity (mm)	Soil Association	Soil Type
ADAS Arthur Rickwood	361	216.0	Fordham/Ireton	Peaty Loam
Buckfast Abbey	463	226.2	Denbeigh 1	Sandy Clay Loam
ADAS Rosemaund	299	265.3	Bromyard	Silty clay loam
ADAS Boxworth	321	222.0	Evesham/Hanslope	Calcerous clay over chalky bolder clay
ADAS Bridgets	315	190.0	Andover	Chalky silty loams over chalk
ADAS Gleadthorpe	294	112.0	Panholes	Loamy sands over sandstone
ADAS High Mowthorpe	359	102.7	Andover	Chalky silty loams over chalk

Sensitivity analysis of the yield model

An analysis of model sensitivity was carried out on the miscanthus biomass to establish the importance of the parameters in this model representation. Since the most sensitive parameters explain most of the variation in the simulated yields, it is these parameters that would direct future modelling and field research. The relative sensitivity of each parameter was evaluated using the following sensitivity function (France & Thornley, 1984):

$$S_i(Y_{dw}, P_i) = \frac{\partial Y_{dw}}{\partial P_i}\frac{P_i}{Y_{dw}} \approx \frac{\Delta Y_{dw}(T)}{\Delta P_i} \times \frac{P_i}{Y_{dw}(T)} \qquad (6)$$

Where S_i is the value of the sensitivity function for a measuring the sensitivity of $Y_{dw}(T)$ to parameter P_i; $Y_{dw}(T)$ is the simulated yield given water limitation at harvest time (T) using the original parameters; P_i is the original parameter value; ΔP_i is a small variation in parameter P_i and $\Delta Y_{dw}(T)$ is the difference between the modelled yield at harvest with and without the parameter variation. If S_i =1, then a given fractional change in the value of the parameter produces the same fractional change in the yield $Y_{dw}(T)$.

Mapping yield across England and Wales

In order to estimate the potential yield across England and Wales, the model was applied to a 30-year time series of daily weather data generated by a stochastic weather generator. The weather generator was parameterised and run for squares on a regular grid of 10 × 10 km (Price *et al*., 2004) and 5 × 5 km using monthly climate values provided by the UKCIP98 (Barrow *et al.,* 1993) and UKCIP02 (Hulme *et al*., 2002), including incident radiation, maximum and minimum temperature and rain days. For this application, the weather generator was modified so that the fraction of extraterrestrial radiation reaching the earth varied between 0.25 on cloudy days and 0.75 on clear days, as used by Thompson *et al*. (1981).

To determine the water-limited yield, the model was applied in the same manner as for the individual sites, with the yields calculated on a grid basis modified via d_f to account for water availability acting as a limiting factor on yield. AWC was calculated using the SEISMIC soils database obtained from the National Soil Research Institute (NSRI) which contained a statistical summary of the soil series present in each 1 × 1 km unit, and their moisture holding capacities (Hallet et al., 1994). Land cover in each 1 x 1 km cell was derived from the ADAS Land Cover Database (Lord, 1998). For cells that contained more than 20% agricultural land, the dominant soil was extracted and the AWC calculated. The AWC values were then averaged over the 10 × 10 km or 5 × 5 km unit.

Modelled yield of miscanthus across England and Wales (5 x 5 km units) under UK climate change scenarios and consideration of other factors that affect yield (Objective 7)

The UKCIP98 and UKCIP02 scenarios, produced in conjunction with the Met Office Hadley Centre, provided information on possible changes in the UK's climate at a regional level and on the potential for changes in extreme weather events (Hulme *et al*., 2002). The scenarios provided detailed monthly data, which were used to drive the miscanthus yield model once statistically representative daily weather data had been generated.

Weather generators

Two weather generators have been used to drive the miscanthus model, the implementation by Friend (1998) of Richardson's (1981) WGEN model (FWGEN) and WXGEN. FWGEN was designed to generate weather for any location, with the required statistical parameters estimated from monthly mean data (UKCIP98). The Friend weather generator had the advantage that that the parameters within the model did not require estimation from long-term weather data because it used the Simmeteo model to estimate parameters from monthly data (Geng *et al*., 1988). WXGEN, a Fortran implementation of Richardson's WGEN (1981) by the USDA/ARS Grassland Soil & Water Research Laboratory, Texas, required parameterisation from long term daily weather data in order to produce simulated site-specific daily weather. The underlying principles of WXGEN were the same as FWGEN and were therefore consistent with the first yield estimates (Price *et al.*, 2004) but because it was parameterised from daily weather data, the standard deviations of the generated weather variables were much more robust and UK specific. There was however, an additional data processing overhead because the statistics which were inherent to the FWGEN had to be estimated from long term daily weather first for WXGEN. WXGEN, once parameterised was used to create statistically representative weather for each 5 × 5 km cell for the baseline period of 1961-1990, 1971-2000 and two future 30-year climate scenarios, centred at 2020 and 2050 (assuming a medium high emissions scenario).

<u>The UKCIP climate scenarios</u>

The UK Climate Impacts Programme (UKCIP), set up in April 1997, is part of a wider programme of research into climate change being undertaken by Defra. Its aim is to co-ordinate and integrate an assessment of the impacts of climate change at a regional and national level. In the first miscanthus model application, the weather generator was driven by the UKCIP98 data for the baseline period 1961-1990 (Price *et al.*, 2004). This has since been superseded by the UKCIP02 (Hulme *et al.*, 2002) scenarios which were developed to address priority concerns including greater regional detail and estimates of changes to extremes of weather and sea level.

Due to uncertainties in future emissions, UKCIP02 presented four scenarios: Low (L), Medium Low (ML); Medium High (MH) and High (H), based on differing assumptions, for three 30-year periods centred on the 2020s, 2050s and 2080s. All the scenarios (L, ML, MH and H) indicated that warming would be greatest in the summer and autumn and greater in the south-east than north-west. In addition, summer and autumn temperatures were predicted to be more variable with temperature extremes also on the increase whilst during the winter, very low temperatures were expected to become less common (Bisgrove & Hadley, 2002).

In order to make use of the monthly UKCIP02 data to generate daily weather on a 5 x 5 km grid, they had to be used in conjunction with data from the Hadley Centre Regional Climate Model 3 (HadRCM3) provided by the Climate Research Unit at the University of East Anglia. These data consisted of daily model runs at a 50 x 50 km grid resolution covering Europe. Daily data were available for the baseline period (1961-1990) and the 2080 scenario period (2070-2100) for the medium-high emissions scenario, (HadRCM3 run A2). Daily data for the other emissions scenarios were only available at the Global Climate Model scale of 300 x 300 km grid resolution, therefore only medium-high (MH) scenarios were run with the miscanthus model. The HadRCM3 daily data at the 50 x 50 km grid resolution was downscaled linearly from 2080 to 2020 and 2050, and upscaled from the baseline period of 1961-1990 to 1971-2000.

The UKCIP02 scenarios used for this project comprised monthly estimates of weather variables on a 5 x 5 km grid. Solar radiation and the frequency of wet days were parameters required for input into WXGEN, but are not provided by the UKCIP02. Therefore, mean solar radiation has been calculated from the mean percentage of cloud cover as supplied by UKCIP02 and frequency of wet days was estimated by assuming the same proportion of change as was evident in the Hadley Centre RCM3 50 x 50 km resolution data. For the baseline period of 1961-1990 and for 1971-2000, the monthly mean data were provided by the Met Office.

To create the input files for WXGEN, each 5 x 5 km cell was assigned to the 50 x 50 km cell in which it was situated. The monthly mean weather variables at 50 x 50 km were then replaced with the monthly mean weather variables at 5 x 5 km. Parameters were not available at the 5 x 5 km and were taken to be the same as at a 50 x 50 km resolution. These parameters were the standard deviations of minimum temperature, maximum temperature, rainfall, and wind speed, the skewness of rainfall and wind speed. In addition, the probability of a wet day following a dry day and the probability of a wet day following a wet day also need resetting at 5 x 5 km and were estimated following the equations of Wilks (1992) using the dependence factor derived from the 50 x 50 km data. In this manner, WXGEN was then used to create 30 years of simulated daily weather for each 5 x 5 km grid cell in England and Wales.

Results and discussion

Objective 1. To determine the yield profile and components of yield at harvest (leaf litter, stem) of miscanthus growing at two densities at seven sites in England, in their post-establishment phase.

Biomass yield

In previous research (NF0403), two components of miscanthus growth were identified; a yield-building phase that lasted for two to five years preceding a plateau phase where yield is maintained. The annual mean yields, for both high and low density planting, for the sites, grouped according to age and yield class, are presented in Figure 1. The results from NF0403 were included to provide long-term yield profiles.

For the Original sites, distinct differences in yields between the two crop densities were evident for the first four years, but for the next three harvests, crop age 5 – 7, yields were similar for the two densities. The Original sites all maintained variable but high yield (Fig 1.a). The mean yield for these three sites for the four years of this study (crop age eight to eleven) was 19.8 odt ha^{-1} (SE = 0.09).

In the New sites, a clear yield advantage with high density planting again occurred for four years and in most subsequent years a small yield advantage was recorded for the high density planting at each site. At the end of the previous project, it was unclear if the New sites with high potential had reached a yield plateau or were displaying an extended yield-building phase. The results here (crop age six to nine; Fig 1.b) indicated that these sites have reached a yield plateau, lower than the Original sites. The New sites with high potential (crop age six to nine) had a mean yield of 17.8 odt ha^{-1} and more seasonal variation than the Original sites (SE = 1.5).

Yield was limited in the New sites with low potential (Fig 1.c). In the current study (crop age six to nine), they produced a mean yield of 12.3 odt ha^{-1} (SE = 1.6). Moisture supply (Gleadthorpe) and temperature (High Mowthorpe) are the two main environmental limiting factors at these sites. These sites are capable of attaining yields of 15 –16 odt ha^{-1} in good years; however, yield reductions of over 50% can occur in adverse years.

Biomass components; height and stem number

Crop height and stem number $area^{-1}$ were investigated to determine how these biomass components were adversely effected by conditions at the low potential sites (Fig. 2). Within the groups, crop height was uneffected by different planting density. Although two years younger, the New high productivity sites attained maximum crop height (mean = 320.7 cm, SE = 7.9) comparable with that of the older sites (mean = 321.9 cm, SE = 3.1). The New low productivity group had crop heights (mean = 236.7 cm, SE = 6.3) lower than that of the New high productivity group of the same age. A difference in final stem number ha^{-1} occurred between low density plots and high density plots in the New sites but did not occur in the Original sites. In the New sites the low productivity group had an overall mean value of 44.6 (SE = 9.5) for final stem number $area^{-1}$ compared to an overall mean value of 62.1 (SE = 5.4) for the New high productivity group.

Biomass components; Standing crop and leaf litter

Current guidelines promote the harvesting of Miscanthus in early spring of the following year rather than in the autumn of the growing season. This practise has a number of consequences. During this period, the standing crop drys down resulting in higher dry matter content at harvest. However, over the winter, some quantity of leaves will become detached from stems. While a proportion of the detached leaves will be incorporated into the bales produced, some will be left in the field and form a mulch. This loss of leaf material reduces the harvested yield from the biomass yield achieved but also reduces herbicide requirement by suppressing weed growth. In the current study, due to plot size, it was not possible to use harvest methods that would be typical of commercial operations. The harvested yields that would have been attained in a commercial, rather than an experimental, situation would have been a little less than reported here but not reduced by the total proportion of leaf litter measured. It was found that the proportion of total biomass produced and accounted for by leaf litter at harvest was unaffected by planting density. Leaf litter varied from site to site and season to season but the differences were not significant. However, a general trend of increased stem to leaf ratio as the crop

Figure 1.a Original sites

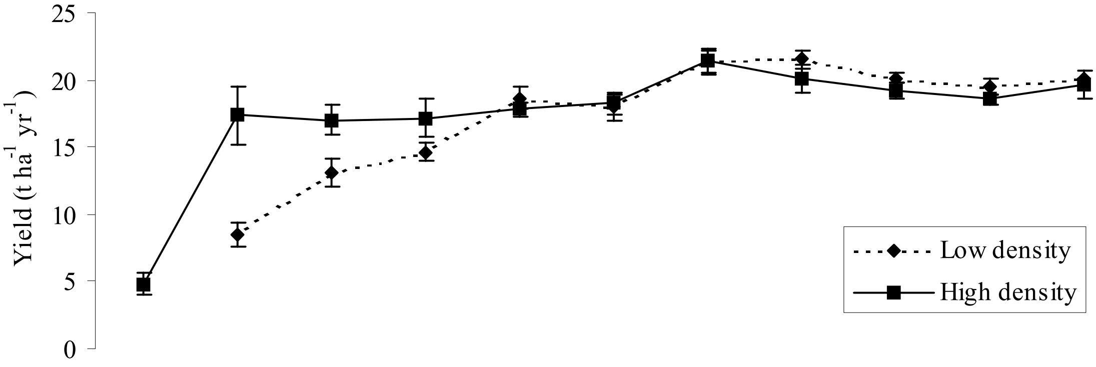

Figure 1.b New sites - High Productivity

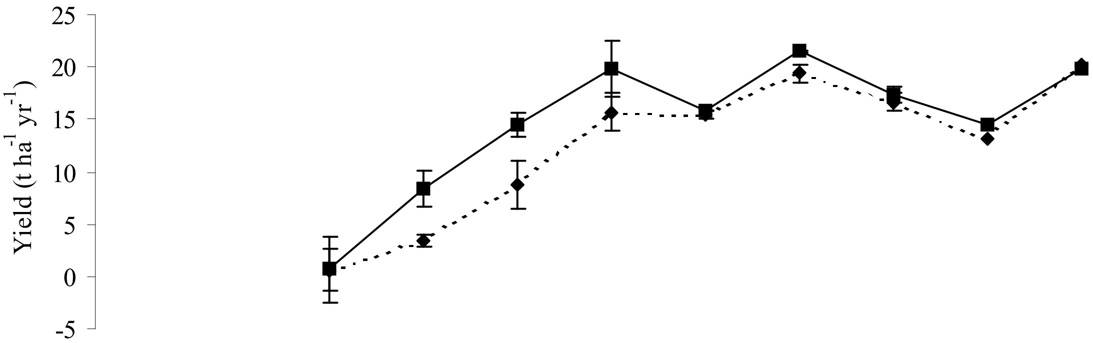

Figure 1.c New sites - Low Productivity

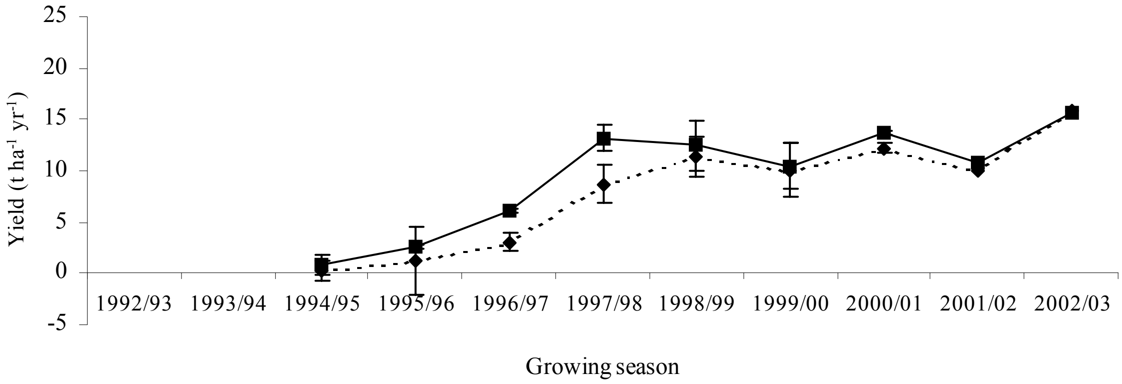

Figure 1. Biomass yield profiles (mean value +/- se) at two planting densities for sites grouped according to age and productivity class.

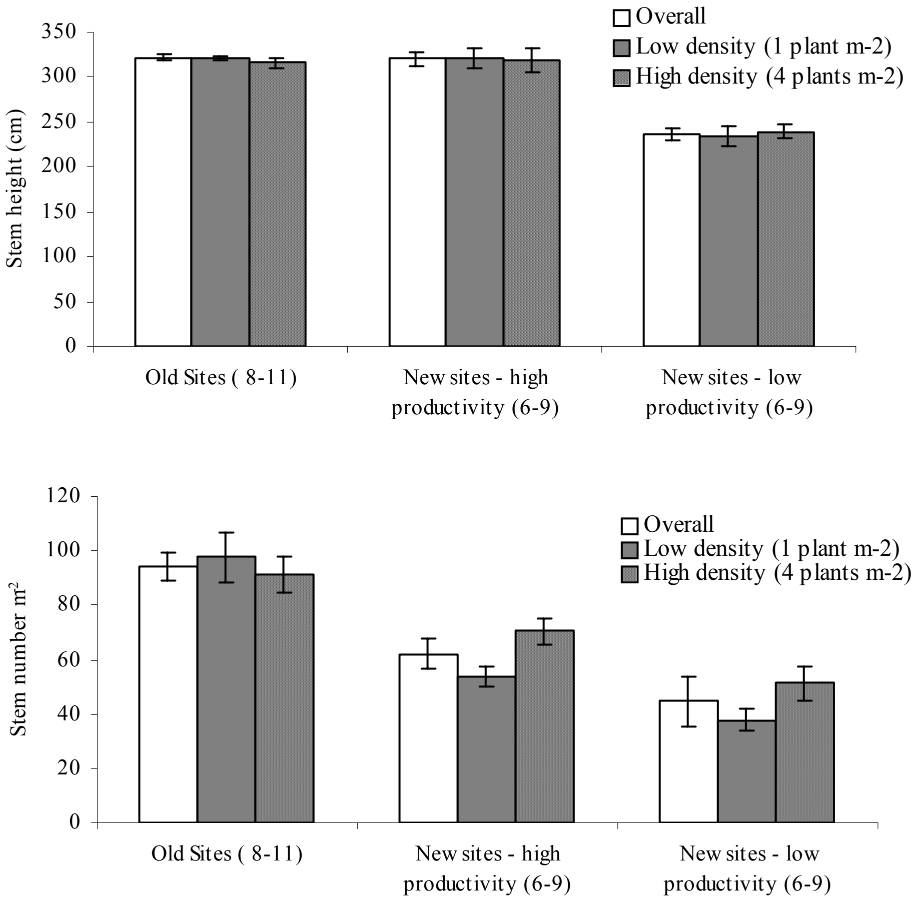

Figure 2. Final crop height and stems number area^{-1} for the site groups averaged over four years

Table 4. Mean contribution of leaf litter to annual yield averaged across four years and two planting densities.

	Crop age (years)	Leaf litter (%)	Standard error
Original sites	8 - 11	20.5	3.1
New sites - High Potential	6 - 9	23.6	2.9
New sites - Low Potential	6 - 9	29.7	4.2
Grand mean		23.9	2.4

aged was noted. This general trend has been noted in other studies (Miscanthus Handbook, 1997). The overall leaf litter mean value was 24 %. The average contribution of leaf litter to yield at the Original sites for crop age 1-7 was 22 % (NF0403) and for crop age 8 – 11 was 20% (Table 4). The average contribution of leaf litter to yield at the New sites for crop age 1-5 was 29% (NF0403) and for crop age 6 – 9 was 26%. These small incremental reductions in percentage leaf litter indicated that the potential loss of harvested biomass due to delayed harvesting was reduced in older crops. However, Gleadthorpe and High Mowthorpe, both New low productivity sites, had the largest proportion of leaf litter contributing to yield, 29.7 % (Table 4).

Objective 2. To identify and, where appropriate, quantify yield loss inducing factors (pests, lodging, and stem basal diseases).

No incidence of pest or diseases influencing yield was recorded at any site during the investigation. When it occurs, stem lodging has the capacity to reduce harvested yield and reduce biomass quality, as lodged stems that are incorporated into bales will have started to degrade. Lodging occurred only in one season, 2001/02, at two sites, Arthur Rickwood and Bridgets. The severity ranged from 10 –17 % and higher levels of lodging occurred in the low density plots than in the high density plots. However, from observations within this study, and the previous study NF0403, it does not appear that lodging is a common occurrence.

Objective 3. To identify key environmental variables, their effect on crop growth and development based on previously determined measures of physiological efficiency

The environmental variables assessed throughout the project were used to parameterise the yield model and are discussed in the results section for Objective 6. However, shoot emergence and early season growth were important determinates of biomass yield and, thus, are discussed here.

<u>Shoot emergence and early season growth</u>
The results from two sites, a high potential site (Arthur Rickwood) and a low potential site limited by temperature (High Mowthorpe), are presented in Table 5 to illustrate the differences in shoot emergence and canopy solar interception characteristics that occurred at these sites and to determine if planting densities effected canopy closure. Shoot emergence date and last frost date were particularly specific to any one growing season. The interval taken to achieve maximum canopy solar interception was dependent on these characters and also on crop age and planting density. To account for crop age differences at the two sites, the dates on which maximum canopy solar interception occurred for that site, rather than direct comparisons of radiation interception at the two sites, were used. The date of emergence, calculated as days from January 1st, was significantly later at High Mowthorpe than at Rickwood. The date that maximum canopy interception was first achieved was also significantly later at High Mowthorpe. Within each site, this character was also significantly different for the two planting densities. The time interval between shoot emergence and maximum canopy solar interception was longer at High Mowthorpe than at Arthur Rickwood. The last frost date was effectively the true start of canopy development as shoot development previous to this date was destroyed by the frost. When the interval between the last frost date and maximum canopy interception was examined it was found to be significantly shorter at Rickwood compared to High Mowthorpe, reflecting higher accumulated daily temperatures at Rickwood after the last frost event.

Objective 4. To maintain the national miscanthus collection.
In 1997, Kew and ADAS, funded by Defra collected wild accessions of miscanthus in the project ‘Collection of natural source miscanthus germplasm from China, Japan, Korea and Twaiwan’ (NFO 404). It was not possible, in the time available, to organise collection tours to China or Taiwan. Consequently, more time was spent in Japan and South Korea. Table 6 summerises the composition of the accessions held at ADAS Arthur Rickwood.

Table 5. Comparison of shoot emergence and early season growth between a high potential site (Arthur Rickwood) and a low potential site limited by temperature (High Mowthorpe) (1999 – 2003).

	Density (plants m^{-2})	Arthur Rickwood High potential	High Mowthorpe Low potential
Dates (Julian date, January 1st = 1)			
Date of shoot emergence	4	79.2	114.5
	1		
s.e.d.		4.5	
Date of maximum canopy solar interception	4	194.3	231.9
	1	203.0	240.0
s.e.d.		4.8	
Time intervals (Julian days)			
Emergence date to maximum canopy closure	4	97.7	115.0
	1	101.1	123.7
s.e.d.		9.6	
Last frost date to maximum canopy closure	4	82.7	126.4
	1	91.5	129.8
s.e.d.		5.1	

Table 6. The number of surviving M. sacchariflorus and M. sinensis accessions maintained at ADAS Arthur Rickwood.

Country of origin	Collected	Number of living accessions	
		M. sinensis	M. sacchariflorus
Japan	111	58	6
Korea	58	40	10

Objective 5. To revise the economic model for miscanthus based on additional growth and yield data.

The revised economic and market analysis provided an update of the analysis undertaken in 1999 (NF0403). This update was opportune as the crop has moved from the position of a potential non-food crop to that where commercial cropping now exists. The introduction of different support structures has resulted in new break-even points for miscanthus production and has changed the profitability of a miscanthus enterprise in comparison to other farm enterprise activities. In the absence of any support, the breakeven cost of production of one baled, oven dried tonne (odt) of miscanthus, the most likely format for energy, is £33.75 ex-farm. The breakeven cost of production of one odt of chipped and dried miscanthus is £55.25 ex-farm, suitable for animal bedding, and one odt chipped and delivered without drying is £51.09, suitable for pulp fibre production. Miscanthus grown for energy can benefit from the Energy Crop Scheme planting grant (£920 ha^{-1}). Including the planting grant in the determination of breakeven costs reduces the price of one odt of baled miscanthus to £26.49. The most developed miscanthus markets are feedstock for biomass energy generation and animal bedding.

From a grower's perspective, miscanthus for energy can be grown on set-aside land or on non set-aside land (with a €45 ha^{-1} $year^{-1}$ EU incentive). An energy Crop Scheme planting grant is currently available. The various support systems were applied to growing miscanthus for energy as a farm enterprise with product value set at £26 odt^{-1}. While all scenarios provide positive gross margins, the only scenario to achieve a positive net margin was with the ECS planting grant and set-aside payments factored in. With no support a minimum product value of £46 odt^{-1} was required to achieve a positive net margin. If grown on non set-aside land and claiming the €45 ha^{-1} $year^{-1}$ EU incentive a product value of £38 odt^{-1} is required for a positive net margin. A general fixed cost of £308 was used to determine these margins and varying the fixed cost value used will, of course, change the profitability. Also, economies of scale are not captured when margins are determined on a hectare basis. The suitability of a miscanthus operation to a specific holding must, of course, be determined on a case by case basis.

The full analysis, including cost derivation, is presented in Annex 1 to this report.

Objective 6. A model of miscanthus yield without and with water limitation and sensitivity analysis of the model

The modelled (both potential and water limited) and measured yields for all seven sites are presented in Table 7. Modelled yields, both potential and water limited, provided a good estimation of measured yields at the Original sites; an average 5% difference between the potential and measured yield at Buckfast Abbey with smaller differences at the other two sites. The modelled values reported are based on the assumption that the crop is established i.e. post the yield-building phase. Typically, the yield-building phase lasted between 3 and 5 years. At the New sites, the actual crop was still in the yield-building phase during seasons 1994-1996 (High Mowthorpe, Bridgets, Gleadthorpe and Boxworth) and, therefore, the modelled yield values were considerably higher than those measured.

The modelled yield values using the new definition of d_f i.e. water-limited yield, were notably improved compared to the initial potential modelled yield values where water availability was not considered. This can be seen generally at High Mowthorpe, Bridgets, and Gleadthorpe and, also, at Arthur Rickwood during 1995 when the effects of drought were observed. At Boxworth, measured yields were typically 18% lower than at Arthur Rickwood, which is also in Cambridgeshire. It was not fully understood why lower yields occurred at Boxworth, but it was thought that perhaps either the AWC available on this heavy clay soil was not correctly estimated or that the crop was not yielding as well as anticipated in the heavy clay due to other soil related factors such as water-logging.

On the free-draining soils of High Mowthorpe and Gleadthorpe, three consecutive years of modelled water-limitation were especially acute (1994/95, 1995/96 and 1996/97). Table 7 displays the effect that this was predicted to have on crops that were post the yield-building phase i.e. water-limited compared to potential predicted yield values at these sites for these years. The drought experienced in these years may indicate that water limitation at the sites had contributed to an extended yield-building phase of miscanthus in the field (5th and 4th seasons at each site, respectively). In comparison, crops planted at Bridgets in 1994 tended towards full potential by the 3rd season.

Daily synthetic climate data for (1962-1990) were used in a sensitivity analysis for the Arthur Rickwood site. The Original parameter values were PAR= 0.5; easily available water = 194mm; rooting depth = 150cm; critical factor = 0.2; wilting factor = 0.05 and maximum crop height = 2.5m (Table 8). Each of these parameters was modified in turn with Δp_i as 5% of p_i. Both RUE and PAR were linear multipliers in the model and, consequently, had the greatest influence on yield. Rooting depth and AWC were also significant within the model, therefore the variation of yield as a function of changes in these parameters has been explored further. The model was run for the synthetic weather data (1962-1990) for different rooting depths in the range 60 – 280 cm where all other parameters were held to the original values (see Figure 3.a). In addition, typical water tensions for a peaty loam, sand clay and sandy clay loam soil were used to calculate a value of easily available water for each of these four soil types using the approach outlined in the methods section. The easily available water parameter was therefore varied in the range defined by these soil types, whilst all other parameters were maintained to their original values and the results are presented in Figure 3.b. The sensitivity analysis confirmed that the model behaved as anticipated, i.e. shallow soils showed the greatest yield variation. The sandy soils also showed the greatest variability in yield, and in the majority of years, the potential yield of the crop on sand was compromised due to water limitation.

Table 7. Measured, modelled potential and modelled yields given water limitation of miscanthus for 7 sites in England and Wales.

Site	Harvestable yield (t ha^{-1} y^{-1} d.m.)	Year 1994/95	1995/96	1996/97	1997/98	1998/99	1999/00	2000/01	2001/02	Average Yield (Years after establishment)
Buckfast Abbey	Potential	24.3	23.2	18.2	18.0	23.0	22.8	24.8	22.6	22.1
	Water limited	24.3	10.8	14.3	18.0	23.0	22.8	24.8	22.6	20.1
	Measured	14.9	19.0	20.2	16.5	19.5	22.2	17.6	17.8	18.4
ADAS Bridgets	Potential	19.7	19.4	18.1	18.7	20.6	20.4	21.7	21.5	20.2
	Water limited	16.3	8.3	13.8	16.8	20.3	20.4	19.2	14.5	17.5
	Measured	0.8	7.9	15.2	19.4	18.1	23.5	16.7	14.5	17.9
ADAS High Mowthorpe	Potential	16.2	15.6	14.9	15.1	16.4	19.9	17.4	17.2	17.2
	Water limited	5.3	5.7	5.7	15.1	16.3	9.7	17.4	3.7	12.5
	Measured	0.5	1.7	4.6	8.5	11.5	8.1	16.0	6.9	10.2
ADAS Arthur Rickwood	Potential	16.8	17.2	17.6	18.5	19.4	22.4	21.2	19.3	19.0
	Water limited	16.8	10.8	17.6	18.5	19.4	22.4	21.2	19.3	18.3
	Measured	16.8	11.7	16.9	20.8	20.3	22.8	20.9	19.6	18.7
ADAS Rosemaund	Potential	17.8	17.2	16.9	17.3	18.7	19.7	20.0	19.3	18.4
	Water limited	17.8	14.7	16.9	17.3	18.7	19.7	20.0	19.3	18.1
	Measured	13.6	17.0	17.6	17.1	24.3	17.5	20.5	19.6	18.4
ADAS Gleadthorpe	Potential	18.1	16.3	15.1	14.9	17.2	19.3	19.2	21.5	18.4
	Water limited	7.3	4.4	4.5	14.9	12.4	8.1	11.6	4.4	10.3
	Measured	0.6	2.2	4.6	13.3	12.4	12.4	9.9	13.8	12.4
ADAS Boxworth	Potential	22.0	17.8	17.6	18.9	19.3	22.4	20.9	20.4	19.9
	Water limited	22.0	10.9	17.6	18.9	19.3	22.4	20.9	20.4	19.1
	Measured	0.5	3.9	8.0	16.2	13.2	17.3	17.3	13.2	15.4

Table 8. The model sensitivity parameters listed in decreasing order of magnitude.

Parameter (*i*)	S
PAR	1.0
Easily Available Water	0.5
Rooting Depth	0.3
Critical Factor 1	0.1
Critical Factor 2	<0.1
Max. Crop Height	0.1

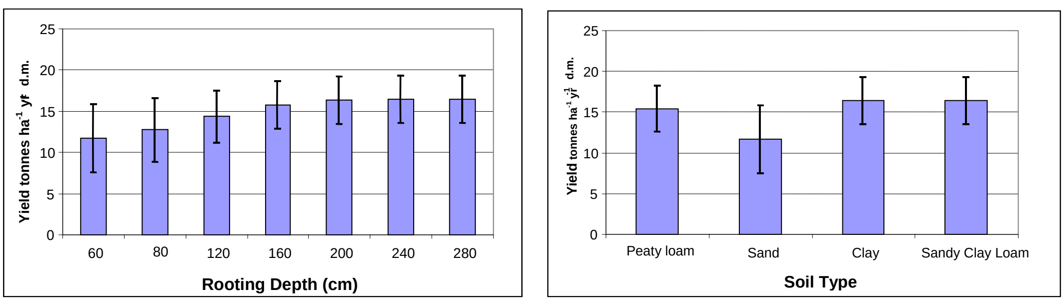

Figure 3. a) Average yield and standard deviation for different rooting depths and b) Average yield and standard deviation for four different soil types for synthetic weather data (1962-1990).

Objective 7. Modelled miscanthus yield for England and Wales at 5 x 5 km, for four climate scenario periods (1961-1990 (Baseline), 1971-2000, 2020 and 2050) and consideration of environmental factors, not used in the model, that effect miscanthus yield.

Figures produced for all four 30-year periods, including potential and water-limited yields, are presented in Annex 2. Key results are presented and discussed here.

The modelled mean, maximum and minimum potential yields for the baseline period (1961-1990) for England and Wales are presented in Figure 4. The average water-limited yields estimated for this baseline period are presented in Figure 5. Lower yields reflected the higher ground, sandy soils and the chalk areas of southern central England. Yield variation across England and Wales was greater for the 1971-2000 period (see Figures on pages 2-4 of Annex 2) than for the baseline period with many areas of the country having larger maximum yields and on average yields were higher across the country.

Figure 6 illustrates the average yields predicted given water limitation, for the 30-year UKCIP02 climate scenario centred on 2050 (Medium-High scenario). On average yields, across England and Wales had increased for both 2020 (presented in Annex 2) and 2050 scenarios with some very high yields > 26 odt ha^{-1} yr^{-1} predicted in the mild regions of south-west England. These predictions did not seem wholly unreasonable as the maximum yield recorded at Buckfast Abbey in North Devon in 1999/00 was 22 odt ha^{-1} yr^{-1}. The crop was still marginal in upland areas of Wales and Northern England and as always, additional limitations such as limited available arable land, slope (cropping access and soil depth) and exposure would render many upland areas unsuitable.

Increasing solar radiation and warmer temperatures (page 5, Annex 2), fuelled the increased yields. The summaries of climate change predicted warmer drier summers (Bisgrove & Hadley, 2002), therefore, it could be anticipated that yields should be reduced due to the high water demand of miscanthus. The average annual rainfall for the 30-year baseline, 1971-2000 and 2020 scenarios did not change dramatically; it was the distribution of the rainfall through the year that was predicted to alter, with more rain in the winter and less in the summer (see page 6 and 7: Annex 2). In the scenarios, drier summers were predicted to occur more frequently, the number of occurrences of 15 or more consecutive dry days (less than 0.1mm rainfall) in August increased for 2020 and 2050 (page 8, Annex 2). This is consistent with field experience, in August 1995, the miscanthus crop at Arthur Rickwood began to senesce and did not recover following 15 days consecutive days without rainfall.

To explain the predicted yields, it was important to consider the changes in other factors that drove the miscanthus model under climate change. It was clear that, as the number of frost days in each season decreased for 2020 and 2050, the average length of the growing season defined in the model increased (see Figures on page 9 and 10 in Annex 2). In spring, growth of LAI in the model was then driven by day-degrees above 6 degrees Celsius and with fewer late spring frosts to kill tender shoots, the modelled crop often began growth in February or March. For the most south-westerly locations, with the assumption that the crop had sufficient water, senescence did not occur until late in the autumn as the growing season was extended. This was feasible as in exceptional circumstances green leaf has been observed at the trial sites all through the winter.

In summary, the mean modelled yield output centred on 2020 and 2050 predicted, on average, good yields, despite the drier summers, for many areas of England and Wales with deep moisture retentive soils. However, sites with shallow, light soils were likely to be increasingly affected by water limitation. This was illustrated by the Figure 7 which presents the number of years in 30 where the modelled water-limited yield was below an economic yield threshold of 12 odt ha^{-1} yr^{-1}. For the 2020 and 2050 scenarios, yields below this economic yield threshold were common on the chalks and light soils areas. For the more moisture retentive soils, greater year to year variability was compensated by good yields in years with longer growing seasons, where rainfall was not too limited. The key for this modelled prediction lied in the earlier emergence of the crop. Warmer spring temperatures, fewer late frosts and increased winter rainfall, allowed the modelled crop to develop quickly in late spring. The crop was most vulnerable to water limitation at the time of rapid yield accumulation which usually occurred in July within the model. For the future climate scenarios, the rapid increase in LAI from 2 to 4 occurred earlier, in June, when water was still available in the soil profile. When the dry period within the model occurred, in August, the crop had in many instances already reached canopy closure. The modelled water-limited yields achieved by the end of June were notably higher for the 2050

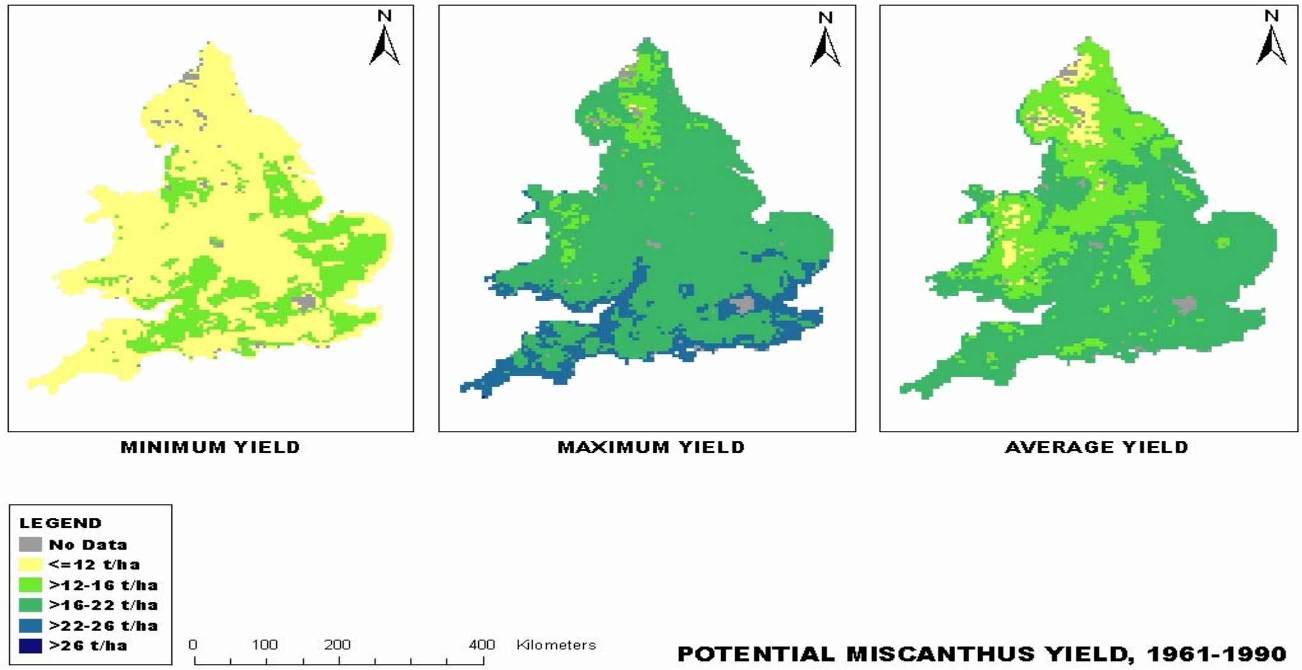

Figure 4: Average, minimum and maximum modelled potential yield (odt ha^{-1} yr^{-1} d. m.) estimated from 30-years of synthetic weather data (1961-1990) for miscanthus on a 5 × 5 km grid of England and Wales.

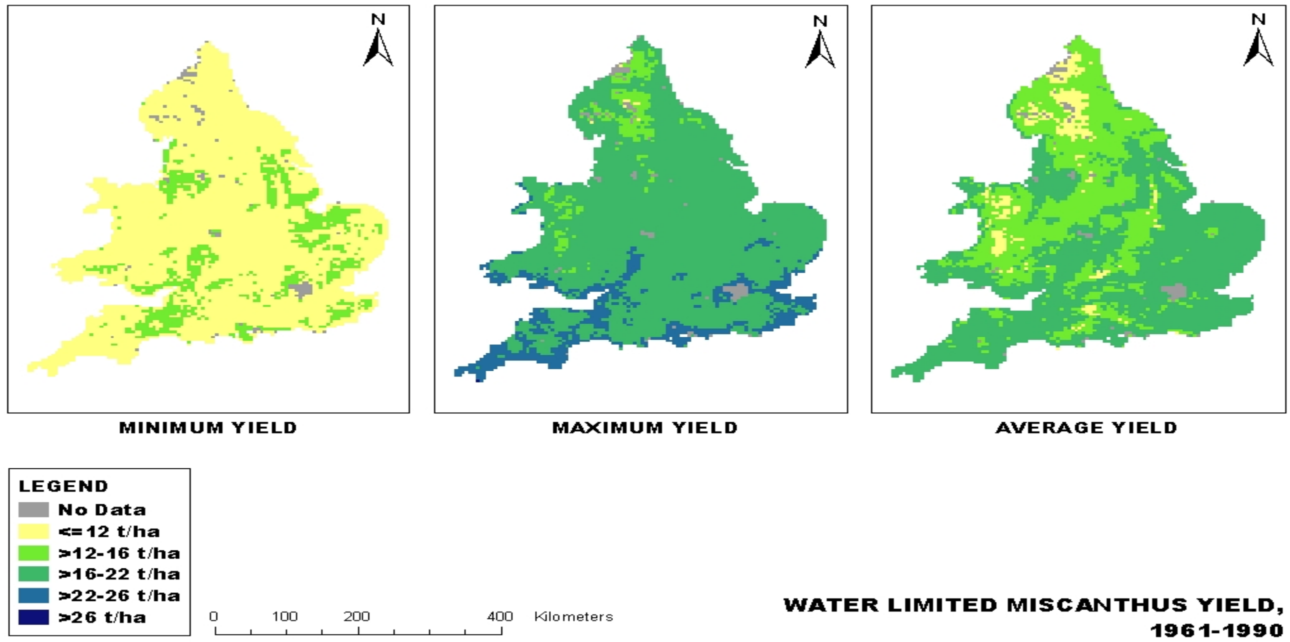

Figure 5: Average, minimum and maximum modelled water limited yield (odt ha^{-1} yr^{-1} d. m.) estimated from 30-years of synthetic weather data (1961-1990) for miscanthus on a 5 × 5 km grid of England and Wales

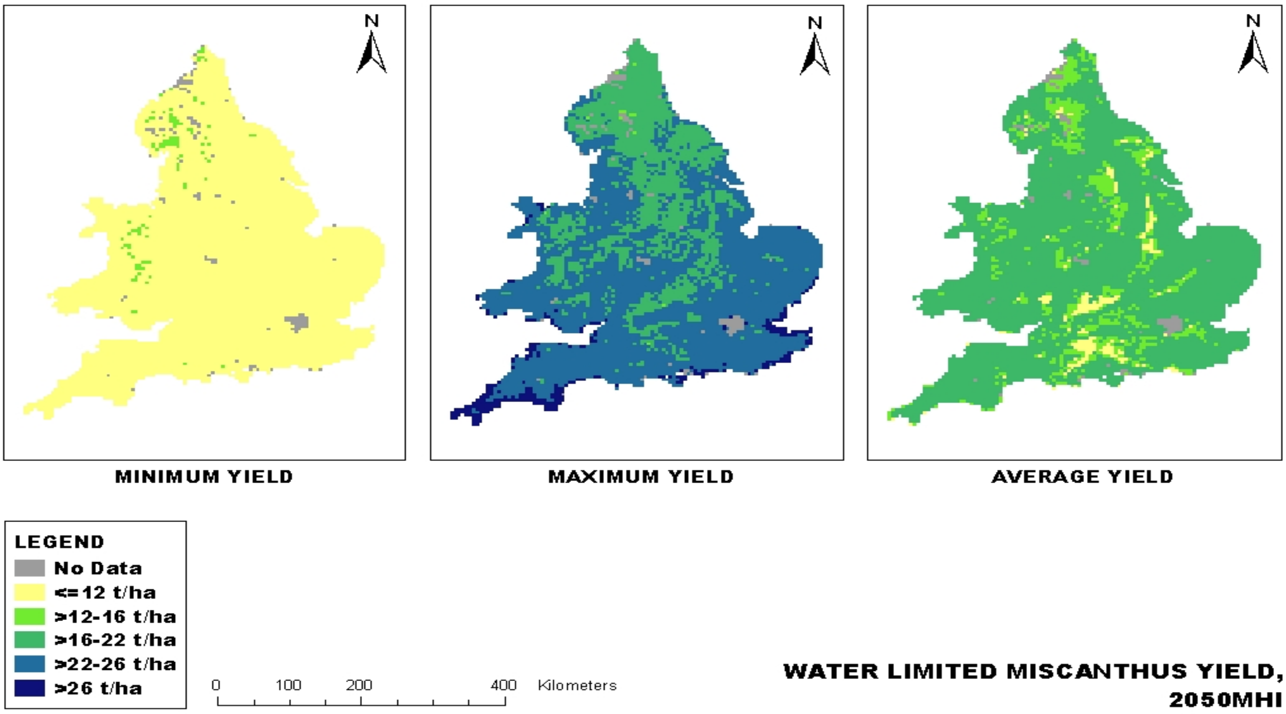

Figure 6: Average, minimum and maximum modelled water limited yield (odt ha^{-1} yr^{-1} d. m.) estimated from 30-years of synthetic weather data centred on 2050 (Medium-High scenario (MHI)) for miscanthus on a 5 × 5 km grid of England and Wales.

scenario than for the other 30 year weather periods (Figure on page 11 of Annex 2). Early senescence and drying of the crop in the dry late summer months may enable Autumn harvesting of the crop to occur which, when possible, can reduce winter losses of biomass and increases the economic viability of the crop (Venendaal *et al*., 1997).

<u>Environmental factors, not used in the model, that effect miscanthus yield.</u>

Factors such as wind, inappropriate soil pH and poor soil structure are known to impose a yield penalty on a wide range of crops. Yield variation and the duration of the yield-building phase of the crop at the ADAS sites have been tentatively linked to some of these factors, yet their magnitude and impact on yield was difficult to quantify given the number of trial sites. Consideration of how these factors may impede on miscanthus yields has been obtained from the literature and suggestions for future inclusion into the model are made, where appropriate.

Soil drainage

Waterlogging of soils can result in an oxygen deficiency in the soil. Damage to plants as a result of poor aeration includes shoot wilt, leaf curl and yellowing, as well as drowned and rotted roots. Under these conditions, available nitrogen is also reduced and it also takes more heat to warm a waterlogged soil, therefore the early growth may be delayed at the beginning of the growing season. Soil drainage is therefore important. The deep roots of miscanthus would penetrate to the depth of mole drains, drawn on heavy soil, disturbing the soil and breaking them down. With a miscanthus crop in the ground for 8-10 years, the drains could not be re-drawn, therefore over time waterlogging could increase. In addition, where the soils are deep enough, the model

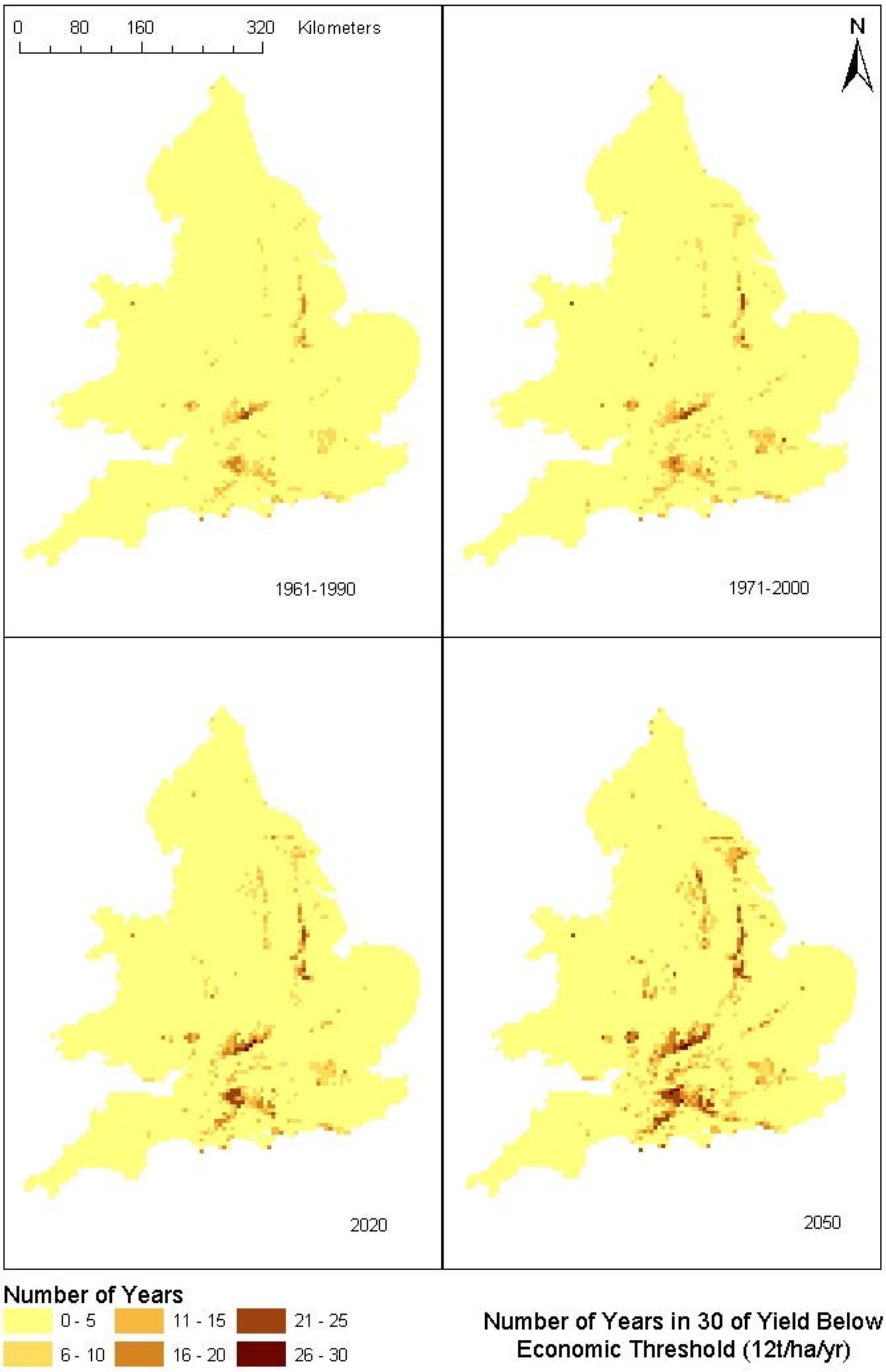

Figure 7. Number of years in 30, where the modelled water-limited yield was below the economic threshold yield of 12 odt ha^{-1} yr^{-1} for each of the 30-year daily weather series generated using the WXGEN weather generator for each 5 x 5 km grid cell across England and Wales. The medium-high climate scenario was used for 2020 and 2050.

assumes that the roots can penetrate the soil to 1.5 m in depth and extract the available water. Soil pans and waterlogged layers may impede the development of miscanthus roots to depth thus reducing the estimated available water. Slowly permeable layers could be identified for a given soil and the rooting depth modifiedwithin the model.

Soil Structure and texture

For miscanthus, Carver (2000) comments that the 'form of the soil aggregate is more important than the soil type'. For soils with poor structure, in the summer when the soil shrinks and cracks into prisms, roots can penetrate between prisms though the availability of water to plants is poor and roots may be exposed to the sun. In addition, the cracks provide rapid pathways for the loss of rainfall to drains, which is not absorbed by the topsoil. During the winter, due to their high water holding capacity, clay soils can be subject to expansion and contraction due to alternative freezing and thawing which can cause also breakage of plant roots.

Soil pH

The literature recommends that miscanthus is grown on soils with an optimum pH range of 5.5-7.5 (Defra best practice guide, 2001). The shallow calcareous soils at ADAS Bridgets and ADAS High Mowthorpe did not appear to impede growth, given that the modelled potential yield was reached in at least one year of the current study. This suggests that miscanthus is fairly tolerant of this factor and pH has not been added as a variable in the model.

Site exposure

Site exposure is a term that may be used to describe factors such as wind speed, wind fetch and frost pockets. Physical leaf damage can arise from leaf tearing and stripping, other wind effects on crops include abrasion and lodging. Whilst Carver (2000) reports wind damage to the tops of the crop, miscanthus is not reported to suffer greatly from lodging. Expansion of the model to calculate solar radiation as a function of aspect could be considered if sufficient site data was available.

Overwintering

Lewandowski *et al.* (2000) reported losses for miscanthus rhizomes in the first winter after planting, with a critical soil temperature of minus 3.5 degree Celsius cited in the literature (Clifton-Brown & Lewandowski, 1998). However, the seven ADAS miscanthus trial sites have not been observed to suffer losses even when temperatures have fallen below this threshold. Therefore, since the model is estimating yield after the establishment phase, yield limitations due to over-wintering are not included.

Conclusions

This study has allowed the continued assessment of yield profiles in sites that were considered either high potential or low potential due to some environmental factor(s) that impacted on yield. Long-term yield profiles are important for both the grower and enduser to address the economics of miscanthus cropping and security of supply, respectively. Stable post-establishment (crop age 8 –11) annual yields have been maintained at the Original sites with very little seasonal, inter-site or planting density differences displayed (mean = 19.8 odt ha^{-1} yr^{-1}, SE = 0.09). Yields from the New high potential sites, although two years younger (crop age 6 –9), were comparable (equal or slightly higher) to those from the Original sites in two of the four years. These New sites were susceptible to reduced yields in years when environmental conditions were less than ideal. The low potential New sites (crop age 6 –9) never achieved yields comparable to the other two groups in any of the four years. In addition to lower average yields, a feature of the New low potential sites was the seasonal variability in yield displayed in this group. In marginal areas of miscanthus cropping, this variability would have a large impact on economic margins for growers and security of supply for end-users.

Comparison of the biomass components crop height and stem number $area^{-1}$ of the Original sites with the New sites indicated that stem number was the component reduced in the New high potential sites and that both crop height and stem number were effected in the New low potential sites. The results showed that within the

New sites (both high and low potential) the plots planted at one rhizome m^{-2} continued to have reduced stem number when compared to the plots planted at 4 m^{-2}. The stem number component may gradually increase with time – resulting in a very long yield-building phase for these groups. This difference in stem number between the two planting densities had disappeared in the Original sites although differences in the time taken to reach canopy closure was apparent at these sites. The persistent differences displayed between the two planting densities in stem number at the New sites highlights the importance of balancing reduced establishment costs (reduced planting density) with subsequent yield reductions at sub-optimum sites. The results from these experimental sites indicated that the increased biomass yield achieved at high density planting in the first 3-5 years of cropping would not justify the extra propagule cost involved in planting at 40,000 rhizomes ha^{-1} compared to 10,000 rhizomes ha^{-1}. However, in a commercial context other factors must be considered; typical establishment rates of 80 %, the cost of weed control in a low density crop and the duration of the yield-building phase at marginal sites. Therefore, a rate of 20,000 rhizomes ha^{-1} is recommended.

The proportion of biomass yield comprised of leaf litter did not display significant differences between planting densities and sites but a general decrease as the crop aged was noted. The leafy morphology of the crop at the New low potential sites indicated that biomass loss (mainly leaf material) due to delayed harvesting may remain typical of a juvenile crop at marginal sites. Continued assessment would determine if the leaf litter proportion at the New low productivity sites will eventually stabilise to a level on par with the other groups or if a higher proportion of leaf loss is a feature of marginal sites. Another factor considered in overwinter leaf loss is the value of the leaf litter to long-term nutrient management. The soluble nutrients contained in the leaf litter are leached back into the soil and provide nutrient recycling, especially for nitrogen (N). Also, miscanthus leaves have a lower energy content than stems so that the biomass yield lost due to delayed harvest is of slightly lower quality than the standing stems. On balance, the benefits that delayed harvest have on reduced inputs (herbicide and nutrients) were considered to outweigh the disadvantage of harvested yield decreases due to leaf loss.

A model of the potential yield of miscanthus has been developed from the data collected from the seven sites. The model developed was simple and parameterised using limited contemporary field data e.g. RUE, LAI and radiation interception from only seven sites. The model was extended to give an estimate of actual yield given water limitation, and this provided a more realistic measure of yields that may be expected. The modification of the drought reduction factor to limit biomass gain when the soil moisture deficit is exceptionally large played a large contribution in this improvement and predicted water-limited yield compared favourably to yield data from the trial sites. Model sensitivity analysis identified the importance of characterising the AWC for a given site in determining water-limited yield.

The model was structured to enable its application with comparatively low overhead for England and Wales (5 x 5 km); therefore, site specific microclimates were not completely captured. Factors outside those used in the model, site exposure, aspect, and soil texture, are considered to impact on yield at a given site and would require detailed information and further work to enable them to be captured in the model. However, the factors used, the weather, soil AWC, crop, RUE and average rooting capacity, required information that was comparatively easily obtained and captured a great deal of the measured yield variability and provided a good modelled estimate of the likely yield of miscanthus.

The importance of maintaining yield in future climate change scenarios was illustrated by the effect of varied yield on the break even cost of miscanthus production (Annex 1). Reduced yields, below 15 odt ha^{-1}, had a steep influence on increasing the BEC as establishment costs and annual husbandry costs are not comparably reduced. For a long-term perennial crop, such as miscanthus, long-term yield profiles and crop modelling provide an indication of whether investment in crop establishment will be profitable. The model has been applied to 5 x 5 km cells across England and Wales. The WXGEN weather generator was parameterised and applied in the model application across England and Wales for 4 scenarios, 1961-1990 (baseline), 1971-2000, and two future 30 year scenarios centred on 2020 and 2050. Weather data for the baseline and future scenarios were entirely modelled and, therefore, uncertainty is inherent. The average yields across England and Wales for the 1971-2000 period showed greater variation when compared to 1961-1990. On average, Miscanthus yields were improved under the predicted future climates, but variability increased; the moisture retentive soils performed well and the droughtier soils less well under increasing stress. On average, the simulated annual rainfall over the 30-year period in the future scenarios (2020, 2050) was similar to levels in the baseline data; however, there was a greater contrast between the summer (drier) and the winter (wetter). The future weather scenarios predicted fewer frost days and, therefore, a lengthened growing season. In addition, solar radiation increased, such that miscanthus yields were predicted to increase where sufficient water is available. Earlier emergence resulted in canopy closure moved to June when, on most occasions, the water availability was not predicted to be critical. In these circumstances, an applied yield threshold (12 odt ha^{-1} yr^{-1} odt) was reached before late summer droughts induced early senescence, this could promote earlier drying and autumn harvesting of the crop.

The relationship between potential yield and water-limited yield was based on a simple function derived from limited data. There is scope for further field or laboratory investigations relating to drought stress responses of the crop to support model validation. The model also assumed that the soil is at field capacity at the beginning of the growing season. Under a future climate, full winter replenishment of the soil profile may not occur. Alternatively, in some areas an increase in winter rainfall could cause problems with waterlogging of roots or restrictions in accessing the field for spring harvesting. Damage to the rhizomes as a result of exceptionally late summer drought is unquantified and any increase in winter waterlogging and root damage may also have an, as yet unquantified, detrimental affect on growth the following year.

In support of further model validation and dissemination of information on the potential yields of miscanthus to growers, the current seven-site experiment should be continued to both identify the duration of the yield plateau phase and also to feed more refined data into the yield model. Additional experiments focused on root performance and crop performance in droughted soils will further refine the model. In particular, a need to understand why yields at Boxworth were lower than the model predicted exists. Further model development and validation is essential to make the most use of the additional experimentation.

Overall, this project has confirmed the ease of husbandry and the yield potential of miscanthus. It indicated that a shift forward in the growing season, earlier emergence and earlier senescence, allowed miscanthus cropping to continue under predicted climate change conditions. The earlier senescence was drought (mid to late summer) induced rather than cold/frost induced. The project highlighted the importance of suitable site selection, both now and under new climatic conditions, particularly in relation to water availability. No significant disease, pest or lodging problems were detected. The plots are a unique resource to monitor the long-term yield profiles of this new crop.

Defra's policy objective in bioenergy is to provide basic knowledge to aid the development of energy crops. This study has continued to do this by demonstrating yield capability of miscanthus and more recently by producing refined yield models and yield maps. The agronomic understanding underpinning this study has fed through to a range of other studies and enabled industry to begin to use the crop commercially. By demonstrating yield with minimal inputs, the work has underpinned Defra's objective of supporting crops that protect the environment at reduced chemical and energy inputs.

References

Allen, R.G., Smith, M., Pereira, L.S. & Perrier, A. (1994). An update for the calculation of reference evapotranspiration. *ICID Bulletin* **43 (2),** 35-58.

Bailey, R.J. & Spackman E. (1996). A model for estimating soil moisture changes as an aid to irrigation scheduling and crop water-use studies: I. Operational details and description. *Soil Use and Management* **12**, 122-128.

Barrow, E.M., Hulme, M., Jiang, T. (1993). A 1961-90 baseline climatology and future climate change scenarios for Great Britain and Europe. *Part I: A 1961-90 Great Britain Baseline Climatology. Norwich: Climatic Research Unit.* **43**.

Bauen, A. (2001) Biomass energy, greenhouse gas abatement and policy integration. *Aspects of Applied Biology, Biomass & Energy Crops* **65**, 353-363.

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.

Bisgrove, R. & Hadley, P. (2002). Gardening in the Global Greenhouse: The Impacts of Climate Change on Gardens in the UK. *Technical Report. UKCIP, Oxford.*

Bullard, M.J. & Nixon, P.M.I. (1999). *M. x giganteus* agronomy for fuel and industrial uses. Final report for project NF0403, MAFF.

Bullard, M.J. & Kilpatrick, J.B. (1997). The productivity of *M. x giganteus sacchariflorus* at seven sites in the UK. *Biomass and Energy Crops, Aspects of Applied Biology* **49**, 207-214.

Bunting, A.H. & Elston, J. (1966). Water relations of crops and grass on chalk soil. *Scientific Horticulture: The Journal of the Horticultural Education Association* **18**, 116-20.

Carver, P.A. (2000). The effect of microclimate upon the growth, photosynthethesis and productivity of *Miscanthus x giganteus* at contrasting plant densites. *PhD Thesis, University of Wolverhampton*.

Christian, D.G., Bullard, M.J. & Wilkins, C. (1997). The agronomy of some herbaceous crops grown for energy in Southern England. *Aspects of Applied Biology*, *Biomass and Energy Crops* **49**, 41-52.

Clifton-Brown, J.C. & Jones, M.B. (1999). Alteration of transpiration rate, by changing air vapour pressure deficit, influences leaf extension rate transiently in *Miscanthus*. *Journal of Experimental Botany* **50(337)**, 1393-1401.

Clifton-Brown, J.C. & Lewandowski, I. (1998). Frosttoleranz der Rhizome verschiedener Miscanthus Genotypen. *Mitteilungen der Gesellschaft fur Pflanzenbauwissenschaften* **11**, 225-6.

Clifton-Brown, J.C. & Lewandowski, I. (2000). Water use efficiency and biomass partitioning in three different *M. x giganteus* genotypes with limited and unlimited water supply. *Annals of Botany* **86**, 191-200.

Defra (2001). Planting and growing *Miscanthus:* Best practice guidelines. *Publication No. 5424.* Department for Environment, Food and Rural Affairs (Defra).

DTI (2001). *Technology Status Report: Biofuels*. HMSO, London.

DTI (2003). *Energy White Paper: Our energy future – creating a low carbon economy*. HMSO, London.

France, J. & Thornley, J.H.M. (1984). *Mathematical Models in Agriculture*. Butterworths, London.

Friend, A.D. (1998). Parameterisation of a global daily weather generator for terrestrial ecosystem modelling. *Ecological Modelling* **109**, 121-140

Geng, S., Auburn, J., Brandsetter, E. & Baoquin, L. (1988). *A program to simulate meterological variables: documentation for SIMMETEO.* Department of Agronomy and Range Science, University of California, Davis.

Hallett, S.H., Thanigasalam, P. & Hollis, J.M. (1994). SEISMIC: an integrated spatial environmental information system for modelling the impact of chemicals. In: *Environmental Modelling the Next Ten Years* (Eds. A.R.D. Stebbing, K. Travis & P. Matthiessen). SETAC 40-49.

Hodkinson, T.R. & Renvoize, S.A. (2001). Nomenclature of *Miscanthus x giganteus* (Poaceae). Kew Bulletin

Hulme, M., Jenkins, G.J., Lu, X., Turnpenny, J.R., Mitchell, T.D., Jones, R.G., Lowe, J., Murphy, J.M., Hassell, D., Boorman, P., McDonald, R. & Hill, S. (2002). Climate Change Scenarios for the United Kingdom: *The UKCIP02 Scientific Report.* Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia**:** 120pp.

Jarvis, M.G., Allen, R.H., Fordham, S.J., Hazelden, J., Moffat, A.J. & Sturdy, R.G. (1984). Soils and their use in South East England. *Soil survey of England and Wales*, Bulletin No. 15, Harpenden.

Lewandowski, L., Clifton-Brown, J.C., Scurlock, J.M.O. & Huisman, W. (2000). *Miscanthus*: European experience with a novel energy crop. *Biomass and Bioenergy* **19**, 209-227.

Lord, E. (1998). Development of an agricultural land use spatial dataset to aid agricultural/environmental spatial modelling and assessment. Final report for project NT2206. MAFF.

Miscanthus Handbook (1997). Contract FAIR 3-CT96-1707. Brussels: European Commission. 178 pp.

Monsi, M. & Saeki, T. (1953). Uber den Lictfaktor in der Pflanzengesellscaften und Seine Bedeutung fur die Stoffproduktion. *Japanese Journal of Botany* **14**, 22-52.

Monteith, J.L. (1977). Climate and the efficiency of crop production in Britain. *Philosophical Transactions of the Royal Society of London* **281**, 277-294.

Neukirchen, D., Himken, M., Lammel, J., Czypionka-Krause, U. & Olfs, H.-W. (1999). Spatial and temporal distribution of the root system and root nutrient content of an established *M. x giganteus* crop. *European Journal of Agronomy* **11**, 301-309.

Price, L., Bullard, M., Lyons, H., Anthony, S. & Nixon, P. (2004). Identifying the yield potential of *Miscanthus x giganteus*: An assessment of the spatial and temporal variability of *M. x giganteus* biomass productivity across England and Wales. *Biomass and Bioenergy* 26, 3-13

Richardson, C.W. (1981). Stochastic simulation of daily precipitation, temperature and solar radiation. *Water Resources Research* **17**, 182-190

Riche, A.B. & Christian, D.G. (2001). Rainfall Interception by mature *Miscanthus* grass in SE England. *Aspects of Applied Biology, Biomass and Energy Crops* **65**, 143-146.

Thompson, N., Barrie, I.A. & Ayles, M. (1981). The Meteorological Office rainfall and evaporation calculation system: MORECS. *Met. Office Hydrological Memorandum* **45**, National Met Office Library.

Wilks, D.S. (1992). Adapting stochastic weather generation algorithms for climate change studies. *Climatic Change* **22**, 67-84

Venendaal, R., Jorgensen, U. & Foster, C.A. (1997). European Energy Crops: A synthesis. *Biomass and Bioenergy* **13(3)**, 147-185.