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Performance of *Miscanthus x giganteus* (Greef et Deu) established with plastic mulch and grown from a range of rhizomes sizes and densities in a cool temperate climate

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ABSTRACT

The effect of biodegradable plastic mulch, rhizome size and planting density on establishment, annual harvested biomass yield of miscanthus and nutrient content were studied at two sites in Northern Ireland. In a split plot experimental design plastic mulch treatment was applied randomly to main plots (covered or left uncovered) after planting rhizome fragments varying in size (by weight) and planting density which were assigned randomly to subplots in four replicated blocks, at each site.

Mean shoot density over both sites was 7.8 and 12.6 m^{-2} for unmulched and mulched in October of the establishment year. Averaged over all sites and planting treatments, uncovered total biomass yields were 0.47, 4.79, 7.74 and 8.12 t DM ha^{-1}, for the first four annual spring harvests, respectively, mulch increasing these yields by 68, 49, 36 and 24%, respectively. Although there were significant effects of rhizome size and density, the effect of plastic declined at successive harvests for large and medium sized rhizomes and high and standard densities. The main effect of plastic mulch was to increase the shoot population density, and shoot number per plant, especially in plants from rhizomes planted at a low number per unit area. Although there were soil moisture deficits in some months, mulching was considered to have improved yields mainly by increasing shoot density due to higher soil temperatures during establishment followed by a mild winter. By the third year, plastic mulch had no significant effect on recommended planting density at all harvests. Plastic mulch had no marked effect on content of N, P or K in biomass.

Covering miscanthus rhizomes with a biodegradable plastic mulch is an effective management tool to increase miscanthus biomass production in a cool temperate climate, at least in the first 3–4 years of production. This is mainly due to increase in soil temperature during establishment and the subsequent year. Mulching allows the optimum planting density of rhizomes to be reduced. Despite additional cost plastic mulch represents an economic benefit to the crop.

1. Introduction

Miscanthus is a genus of tall erect grasses in the Poaceae family native to south east Asia. Having a C4 photosynthetic system it captures carbon dioxide more efficiently than the C3 system common to most dicotyledonous and monocotyledonous species of temperate origin. The C4 system also confers the capability to photosynthesise at higher temperatures and increased tolerance to low content in soil moisture and mineral nitrogen than a C3 system. However, contrary to most species with C4 systems, miscanthus is capable of producing high yields of lignocellulose in temperate environments such as in the southern half of England and the south of Ireland (Clifton-Brown et al., 2001). Studies on the development of *Miscanthus giganteus* have shown that the threshold temperature for leaf elongation is 6 °C, however, under field conditions crop growth may be slow at air temperature less than 10 °C (Clifton-Brown et al., 2000). Although experimental trials have shown that miscanthus might be able to produce commercially viable biomass yields under the climatic conditions of the northern part of Ireland (Easson et al., 2011; Caslin et al., 2015), slow growth during its establishment phase represents a challenge to encouragement of commercial planting. Mean long term air temperatures for the warmest month in summer is 2 °C higher for Cambridge in the east of England than for Aldergrove, near Belfast in Northern Ireland, although mean temperatures for the coldest month (January) are similar at 4.3 °C, with

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the lowest extremes recorded of −17.2 °C (from 1914 to 2007) and −15 °C (from 1927 to 2014), respectively. (http://www.metoffice.gov.uk/climate/uk/regional-climates).

While the LT_{50} (Lethal temperature, temperature at which 50% of the sample is killed) for rhizomes of *Miscanthus giganteus* has been found to be at soil temperature of −3.4 °C at 5 cm depth in a young crop, they are able to withstand lower temperatures over subsequent winters as adequate shoot buds are sufficiently deep in the soil as the rhizomes develop to avoid hard frosts (Clifton-Brown and Lewandowski, 2000).

Covering newly planted maize, which is also a C4 plant, with plastic mulch can have a marked beneficial effect on spring growth of the crop in Northern Ireland (Easson and Fearnehough, 2000, 2003). Average air and 5 cm soil temperatures under plastic mulch for the first 70 days after planting under mulch can be elevated by more than 5 °C and 2.5 °C, respectively (Easson and Fearnehough, 2003). Unlike maize, miscanthus is a perennial crop and so in addition to establishment, overwintering is important in its production. Therefore covering the soil immediately after miscanthus rhizomes are planted in spring could accelerate the development of the crop at more northerly latitudes, improving its establishment and ability to withstand conditions over the first winter. Although miscanthus is considered to use soil water efficiently (Long and Beale, 2001) water availability can limit miscanthus biomass production in England and Wales (Price et al., 2004; Richter et al., 2008). However, compost mulch applied to the soil surface after planting miscanthus can retain soil moisture and improve establishment (Davies et al., 2011).

Management options to compensate for cool temperate conditions, and especially to aid establishment in the more northerly parts of the British Isles, include increasing rhizome number (Atkinson, 2009) and weight (Khan et al., 2011) to increase shoot number. However, Farrell et al. (2006) have shown biomass yields of miscanthus grown in climates such as in north western Europe are limited due to late emergence of shoots caused by low spring temperatures and late spring frosts.

The following study in Northern Ireland was carried out to investigate the effect of covering a newly planted crop of miscanthus with plastic mulch on its development during establishment. As it is hypothesised that shoot number would be increased during establishment due to mulch the effect was studied in association with a range of rhizome sizes and densities to investigate if use of mulch would allow fewer and/or smaller rhizomes to be planted without loss of biomass.

2. Materials and methods

2.1. Description of sites

The experiment was carried out at two sites, i.e. Hillsborough (lat 54.48° N, long 6.08° W) and Loughgall (lat 54.4° N, long 6.6° W). Most of the detailed study was carried out at the Hillsborough site while biomass production, mean shoot mass and shoot density at spring harvests were determined at both sites. The sites were formerly grassland (mainly perennial ryegrass *Lolium perenne* L.). The soils, based on the classification of Avery (1980), were Surface Water Gley (Class 1) on Shale Till (SWG1ST) at Hillsborough and Brown Earth on Red Limestone Till (BERLT) at Loughgall. At both sites grass was sprayed off with roundup, ploughed and rotavated twice immediately prior to planting the rhizomes in May 2007. Subsequently land was levelled with a land leveller and Cambridge roller. No fertiliser was applied to either site throughout the experiment.

2.2. Treatments

The trial comprised of 72 plots (7.5 m × 10 m each) of *Miscanthus x giganteus* in a randomised split plot design at the two sites with four replicated blocks at each site of which main plots had either plastic mulch laid after planting (Mu) or remained uncovered i.e. no plastic mulch (NMu). Nine subplots were randomly assigned within each main plot comprising a factorial arrangement of three rhizome size treatments and three rhizome density treatments. Rhizomes for planting were excavated manually by fork in April 2007 from miscanthus originally planted in 2003, and stored at 3 °C until they were sorted before planting into three size fractions with average fresh weights of 25 g, 75 g and 225 g (± 10%) i.e. Small (Sml), Medium (Med) and Large (Lrg) rhizome fragment ('rhizome') size treatments, respectively. Rhizomes were planted in shallow furrows which were opened up with a drill plough in rows 67 cm apart in each plot at low (LD), standard (SD) and high (HD) densities equivalent to 1350 g, 4050 g and 12,150 g per plot, respectively, (i.e. 180, 540 and 1620 kg ha^{-1}). This resulted in planting per plot Sml, Med and Lrg rhizomes at LD with 54, 18 and 6 rhizomes, respectively, 162, 54 and 18 rhizomes at SD and 486, 162 and 54 rhizomes, respectively, at the HD. Planting rates are presented in Table 1.

Table 1
Rhizome planting rate ('000 ha^{-1}) for each treatment.

Rhizome size	Rhizome density ('000 ha^{-1})		
(g)	LD	SD	HD
Small (25 g)	7.2	21.6	64.8
Medium (75 g)	2.4	7.2	21.6
Large (225 g)	0.8	2.4	7.2

The rhizomes were covered with soil to a depth of approximately 7.5–10 cm. Immediately after planting bio-degradable plastic mulch was applied to the mulch treatment plots (Mu) with a single row mulch layer (X − TEND) supplied by Samco Agricultural Manufacturing Ltd., Republic of Ireland. The plastic mulch used consisted of a 6 µm film without perforations degradable by natural light and temperature allowing the plastic film to be broken down in the soil. Simultaneously a combined active herbicide mixture, comprising Stomp (active ingredient, a.i., pendimethylin) at 2.5 l/ha and residual Calaris (a.i. mesotrione and terbuthylazine) at 1.5 L ha^{-1}, was applied with a ground wetting agent at 0.4 L ha^{-1}. All plots were treated with Roundup Energy (a.i. Glyphosate) at 3.2 L in 300 L water ha^{-1} after the spring harvest in April 2008 and 2009 at both sites.

2.3. Assessments

In the autumn prior to planting, soil at the Hillsborough site was sampled for mineral analyses. Phosphorus was analysed by the Olsen method (MAFF, 1986) and minerals by inductively coupled plasma atomic emission spectrometry (ICPAES). Indices for nutrient content are taken from DEFRA, 2010. Results were pH 6.53, P 29.6 mg P kg^{-1} (Index 3), K 343 mg K kg^{-1} (Index 3), Mg 102 mg Mg kg^{-1} (Index 3) and 7.97 mg S kg^{-1}.

Rhizome viability was assessed by counting the number of rhizomes that had produced shoots in the establishment year at Hillsborough and Loughgall on 7 and10 August, respectively, on three 10 m lengths of drill on SmlSD, SmlHD and MedHD plots and in the whole plot for the remaining treatments. In 2007 on 11 occasions, number of emerged shoots were counted on three 10 m lengths of drill per plot or the whole plot, as described for assessing viable rhizomes, and converted to shoot population density (shoots m^{-2}). For LrgLD (6 rhizomes planted per plot) 2 plants per plot were selected at random and harvested at cutting height and for MedLD and LrgSD (18 rhizomes planted per plot) 6 per plot were sampled in the same way. Harvesting of miscanthus plants was carried out at two intervals every year (spring and autumn) for both sites in 2008, 2009, 2010 and 2011 and harvested yield was determined by calculating the yield per plant, multiplying that weight by the number of viable rhizomes per plot and by 136.3 to arrive at kg DM ha^{-1}. Two randomly selected 2 m lengths of rows X 0.67 m wide were sampled in each plot in the remaining treatments and yield per ha determined by multiplying the dried weight harvested (in kg) by 3748. The treatments planted with 6 or 18 rhizomes per plot were excluded from estimation of yield in the spring sampling in 2009 and each October from 2008 to 2010. Biomass production from each was much lower than from the other treatments and as resources were limited on these occasions it was considered that these treatments could be sacrificed on these occasions. In retrospect, all plots should have been sampled in the spring 2009, as had been done in other years.

Shoots per rhizome were calculated from number of shoots per ha at spring harvests in 2010 and 2011 at both sites, divided by density of viable rhizomes (no. ha^{-1}) at August 2007. The shoots were bundled and weighed fresh. Five shoots were taken at random, divided into stem and attached laminae, the components weighed fresh and subsamples taken to be dried to determine dry matter content of the components. From the fresh weight and DM content of the components and the fresh weight of the samples harvested, the content of DM comprising stem, mean shoot DM weight and DM yield were calculated.

Subsequent to sampling in spring each year all plots were cleared off with a Kemper head harvester, close to ground level.

At harvests in spring 2008 and 2011 and autumn harvest in 2010 dried shoots were chemically analysed for Nitrogen (N), Phosphorous (P) and Potassium (K). Loss of N, P and K over winter of 2010/11 was determined by calculating the difference in offtake between the autumn 2010 and spring 2011 harvests. Dried milled samples underwent standard laboratory concentration analysis for N by Dumas method, Elementar VarioMax CN) and, after wet digestion, P by Flow injection analysis and K by Atomic emission spectroscopy.

2.4. Statistics

Differences in treatment means were tested for significance by ANOVA using Genstat (16th Edition. VSN International, Hemel Hempstead, UK). The data sets for the 4 blocks in each of the two sites were combined and analysed as a split plot randomised block design in 8 blocks with Mulch as the main plot treatment and Rhizome density and Rhizome size as the randomised subplots treatments. When the treatments planted with 6 or 18 rhizomes per plot were omitted, the low density treatment was removed from the analysis, sacrificing the SmlLD data which had been collected and treating absent LrgSD as missing values.

To take account of the different methodologies used to measure biomass and shoot numbers the data was weighted to ensure that measuring different areas on different plots would not affect the results so each weight would be proportional to the reciprocal of the expected values for the corresponding unit. Where there were significant treatments effects the means were compared using Least Significance Difference (LSD). Differences between sites could not be tested as there was no independent replication of the sites, and so sites were regarded as random effects.

2.5. Meteorological conditions

Daily maximum and minimum air temperature and rainfall data were collected manually at each site. Meteorological data required for calculation of daily reference evapotranspiration (ETo) i.e. wet and dry bulb air temperature, solar radiation and wind speed, were collected hourly by a Campbell weather station at Hillsborough (within 500 m of the trial site). Calculation of daily ETo followed the method of Zotarelli et al. (2013).

During the establishment period i.e. March to October 2007 when plastic mulch was obviously covering the soil after planting, rainfall was higher during June and July of 2007, than during the rest of the growing season that year (Fig. 1a).

The rainfall and reference evapotranspiration (ETo) for each month during the growing season (from March to October) at Hillsborough (data to calculate ETo at Loughgall were not available) are presented in Table 2. Mean precipitation for the growing season exceeded that of the ETo by 198.5 mm (averaged over the four years). Accumulated deficits in successive months in which ETo exceeded precipitation were 89.5, 157.6, 37.3 and 59.3 mm in 2007, 2008, 2009 and 2010, respectively.

During the three growing seasons for the established stands (2008–2010) the mean daily temperature (average of daily maximum and minimum) for both sites was 12.0, 12.6, and 12.5 °C, respectively (Fig. 1 a). The mean daily air temperature from November to March for each winter from 2007 to 8 to 2010–11 was 6.4, 4.9, 3.6 and 3.7 °C, respectively. Outside the growing season, 2010 was the coldest year during the experiment, having the lowest air temperatures during winter 2009–10 in January to March and later in the year in November and December. Mean monthly rainfall for both sites was 88, 79, 80 and 73 mm for the years 2007–2010.

Soil temperature under mulch during the growing season in the first year, when mulch was mainly intact, was estimated from soil temperature at 10 cm in the open applying the equation of Easson and Fearnehough (2000) for soil temperature at 5 cm i.e.

$$y = 0.022x + 2.96 \quad (1)$$

in which y is the increase in soil temperature due to mulch (°C) and x is incident radiation ($W\ m^{-2}$) (Fig. 2). Soil temperature under mulch was estimated to be 5–10 °C higher than that in open plots.

3. Results

Generally, the average for both sites is presented unless there is justification for presenting site means separately (viable rhizomes planted and shoot population density counted at intervals during year of planting).

3.1. Establishment

The establishment phase was taken to be the period from planting to the first harvest in early spring of the following year. Calculated loss of moisture, relative to precipitation, was greatest during the first half of the growing season in 2007 (Table 2). The first winter, i.e. the winter during establishment, was the mildest of the five winters during the trial with the mean minimum air temperatures for all of the months during that winter remaining above zero (Fig. 1a) and b). During that winter 22 days had air temperature below 0 °C, with minimum temperature for only one day falling to as low as −3 °C

Over all treatments, 86% at Hillsborough and 92% at Loughgall of planted rhizomes produced shoots in the establishment year (Table 3). Mulch had no significant effect on these percentages but the proportion of Sml rhizomes producing shoots was significantly ($P < 0.001$) lower than that of the other two larger Med and Lrg rhizomes at Hillsborough.

During the establishment year shoot density increased markedly due to treating with mulch, particularly after mid-July (Fig. 4). Shoot production in the crop as a whole reached a plateau by late August-early September when the mulched treatment had approximately double the number of shoots of the unmulched treatment. Significant interactions ($P < 0.001$) between mulch and rhizome size and mulch and rhizome density were due to mulch having a greater effect on shoot number m^{-2} in treatments with large than smaller rhizomes (Fig. 3 a and c). At Loughgall, shoots were counted from late August, corresponding to the 7th count at Hillsborough (Fig. 4a) to d). As at Hillsborough the shoot population density was approaching its maximum for all treatments from this time. The scale of differences between the treatments was similar to that for the Hillsborough site although the positive effect of mulch was less than at Hillsborough.

Comparing the progress in shoot population density during the establishment year in treatments with the same rhizome planting rate at both sites (7200 ha^{-1}; SmlLD, MedSD and LrgHD), the proportionate

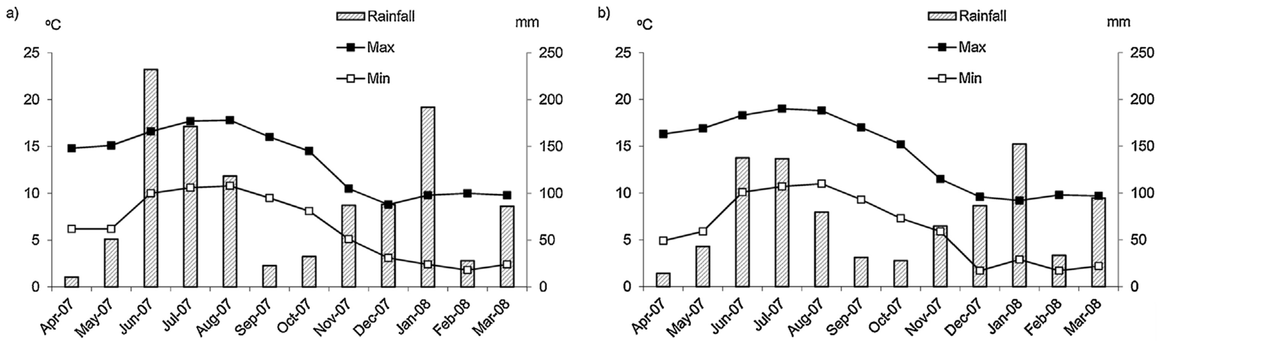

Fig. 1. Mean monthly maximum and minimum air temperature and monthly rainfall at a) Hillsborough and b) Loughgall during establishment of miscanthus (April 2007–March 2008).

Table 2
Mean monthly reference evapotranspiration (ETo, mm) and precipitation (Ppt., mm) during the growing season 2007–2010.

Month	2007		2008		2009		2010	
	ETo	Ppt.	ETo	Ppt.	ETo	Ppt.	ETo	Ppt.
March	–	–	41.6	86.2	41.0	42.0	n/a	77.5
April	66.8	10.5	60.0	14.8	57.9	88.9	46.8	40.2
May	84.1	50.9	95.1	13.3	68.0	81.7	61.5	35.3
June	80.0	232.1	86.0	55.3	81.3	46.8	71.8	45.3
July	80.1	171.3	79.4	124.9	73.2	127.6	62.0	140.8
August	70.8	118.4	59.0	205.6	56.4	123.7	57.3	44.8
September	47.8	22.7	41.7	87.5	38.0	35.2	39.3	133.0
October	21.8	32.4	19.1	109.9	14.1	55.2	23.4	63.4

increase due to mulch was similar for all rhizome sizes, but the arithmetic increase due to mulch increased with rhizome size (Fig. 3b and d). At both sites the shoot population density in the MuLrgHD treatment reached a plateau at almost 16 m^{-2}, compared to the NMuSmlLD treatment that reached only about 3 m^{-2} during the same period (Fig. 5).

3.2. Biomass yields

Biomass yields averaged over all treatments for the four annual spring harvests after the establishment year were 0.63, 5.50,9.15 and 9.09 t DM ha^{-1} (Table 4). In each year mulch and rhizome size and density had significant ($P < 0.001$) effects on yield. The average positive effect of mulch over all treatments in the four years was 1.6 t DM ha^{-1}, although in the third year the response was 2.8 t ha^{-1}. Increasing rhizome size had an inverse effect on yield. Nine times more Sml rhizomes than Lrg rhizomes were planted within the same density treatment but produced only 2.3 times the yield of the large rhizome treatment. Yield was positively related to density (by weight), the relative response declining with age (Table 4), with such effect still being statistically significant after four years since the crop was planted.

Table 3
Main treatment means for proportion of rhizomes planted that produced shoots by August in the year of planting (2007) at both sites.

Variable	Proportion of planted rhizomes with shoots
	Both sites
Mulch	
NMu	0.90
Mu	0.88
Sig	ns
LSD	0.028
Rhizome size	
Small	0.85^{b}
Medium	0.91^{a}
Large	0.90^{a}
Sig	**
LSD	0.039
Rhizome density	
LD	0.90
SD	0.89
HD	0.87
Sig	ns
LSD	0.039

Means in the same column for a given variable followed by different superscripts are significantly different. No interactions were significant.LSD = least significant difference; ns = not significant, ** = P < 0.01.

Two way interaction tables of means are presented in Table 5. In the first two years the interaction between mulch and rhizome density was significant ($P < 0.001$ and $P < 0.05$). In 2008, mulch had a greater effect on yield at HD than LD (increase of 0.6 and 0.1 t DM ha^{-1}, respectively) while in 2009, when the lowest density was omitted, mulch increased yield by an average of 4 t DM ha^{-1} in the standard density compared to 0.7 t ha^{-1} in the high density treatment. A significant mulch x rhizome size interaction was due to mulch having no effect on yield from the Med rhizomes compared to a benefit of 3.2 and 3.8 t DM ha^{-1} in Sml and Lrg rhizome crops.

At harvests in spring 2010 and 2011, the mulch x rhizome size x

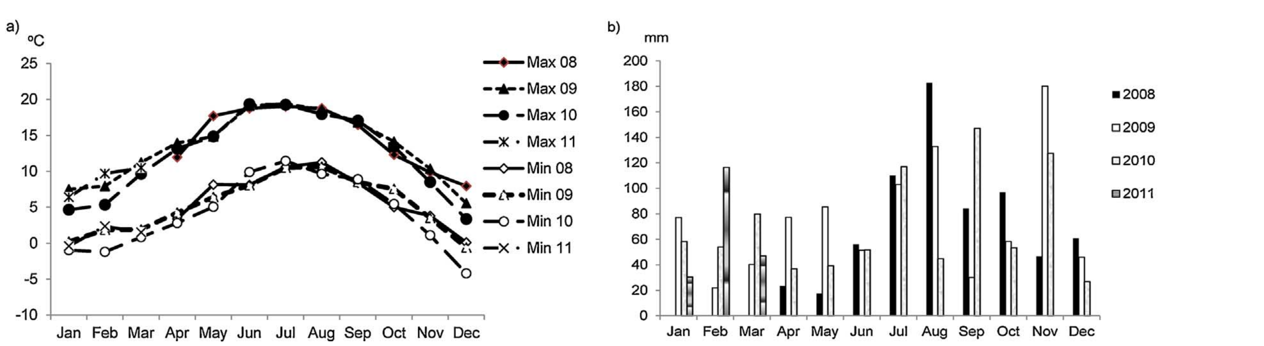

Fig. 2. a) Mean daily maximum and minimum air temperature for each month and b) monthly rainfall from April 2008 to March 2011(averaged over both sites).

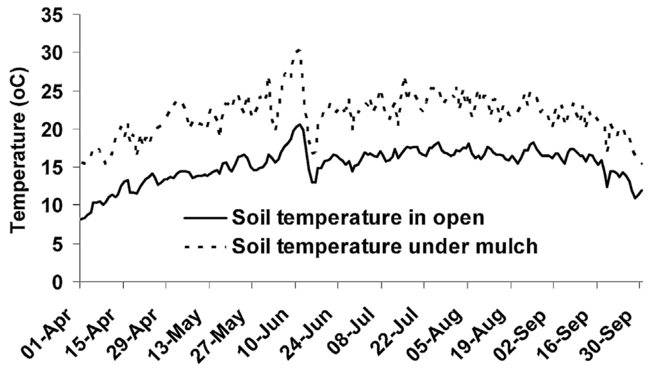

Fig. 3. Soil temperature at 10 cm measured in the open and estimated under mulch from 1 April to 30 September in 2007.

rhizome density interaction was significant ($P < 0.05$ and $P < 0.01$ in 2010 and 1011, respectively). These interactions were due to mulch increasing biomass production in the following treatments in spring harvest 2010: SmlLD (5.04 vs 9.69 t ha^{-1}), SmlSD (10.01 vs 16.79 t ha^{-1}), MedSD (7.52 vs 12.69 t ha^{-1}) and LrgHD (9.25 vs 12.98 t ha^{-1}). Corresponding significant effects of mulch at Spring harvest in 2011 were: SmlSD (11.93 vs 14.83 t ha-1) MedSD (7.37 vs 12.91 t ha-1) and LrgHD (9.62 vs 14.49 tha^{-1}). So in 2010 all treatments planted with 7200 rhizomes ha^{-1} were the most responsive treatments to mulch for each rhizome size treatment along with the smallest rhizomes at the standard rate (21,600 ha^{-1}). At spring harvest in 2011, of the two small rhizome treatments, biomass production of only that planted at 21,600 ha^{-1} significantly responded to mulch. The significant interaction between mulch x size x density at spring harvests in 2010 and 2011 (Table 5) was mainly due to mulch having the greatest effect in both years on SmlLD, MedSD and LrgHD i.e. at planting density of 7.2×10^3 rhizomes ha^{-1}, although there was also a marked positive effect of mulch on SmlSD in 2010.

3.3. Shoot weight and population density

Shoot weights were assessed at spring harvests from 2009 to 2011. Averaged over both sites, mulch had no significant effect on shoot weight although mulch x rhizome size and mulch x rhizome density interactions at the 2009 harvest were significant (Table 6). Mulch resulted in production of heavier shoots from the large rhizomes compared to all other shoot size/mulch treatments (response of 11.1 g DM compared to mean of 0.2 g over the two smaller rhizome treatments) and mulch overcame the adverse effect of the lower rhizome density on shoot weight (increasing weight of SD shoots from 20.6 to 30.1 g). Significance of rhizome density effect on shoot weight in all three years was due, in general, to higher shoot weight in the high than low density treatment, while at the 2010 harvest the smallest rhizomes produced lighter shoots than the other two size treatments.

Shoot population density, determined at spring harvests in 2010 and 2011, was significantly higher in the mulch than non-mulch treatment (by 23%, $P < 0.001$) over all rhizome treatments (Table 6). The significant mulch x rhizome density interaction was due mainly to mulch having a marked positive effect on shoot weight in SD in 2010 (increase of 9.6 g DM compared to an average of 2.3 g over the other two density treatments) and on SD and HD in 2011 with an average increase over the two higher density treatments of 7.8 g compared to 0.8 g for LD. Increasing rhizome size from Sml to Lrg, or reducing rhizome number per unit area, reduced shoot density by more than one half. Increasing rhizome density from LD to HD increased shoot number by an average 2.6 times.

3.4. Shoots per plant

Although in this study rhizome density was based on total fresh rhizome biomass planted per ha, mean shoot number per plant at rhizome densities based on rhizome number per ha are presented in Table 7. In 2007 when the viability of rhizomes planted was assessed, mulch had a positive effect on shoots per plant (significant at

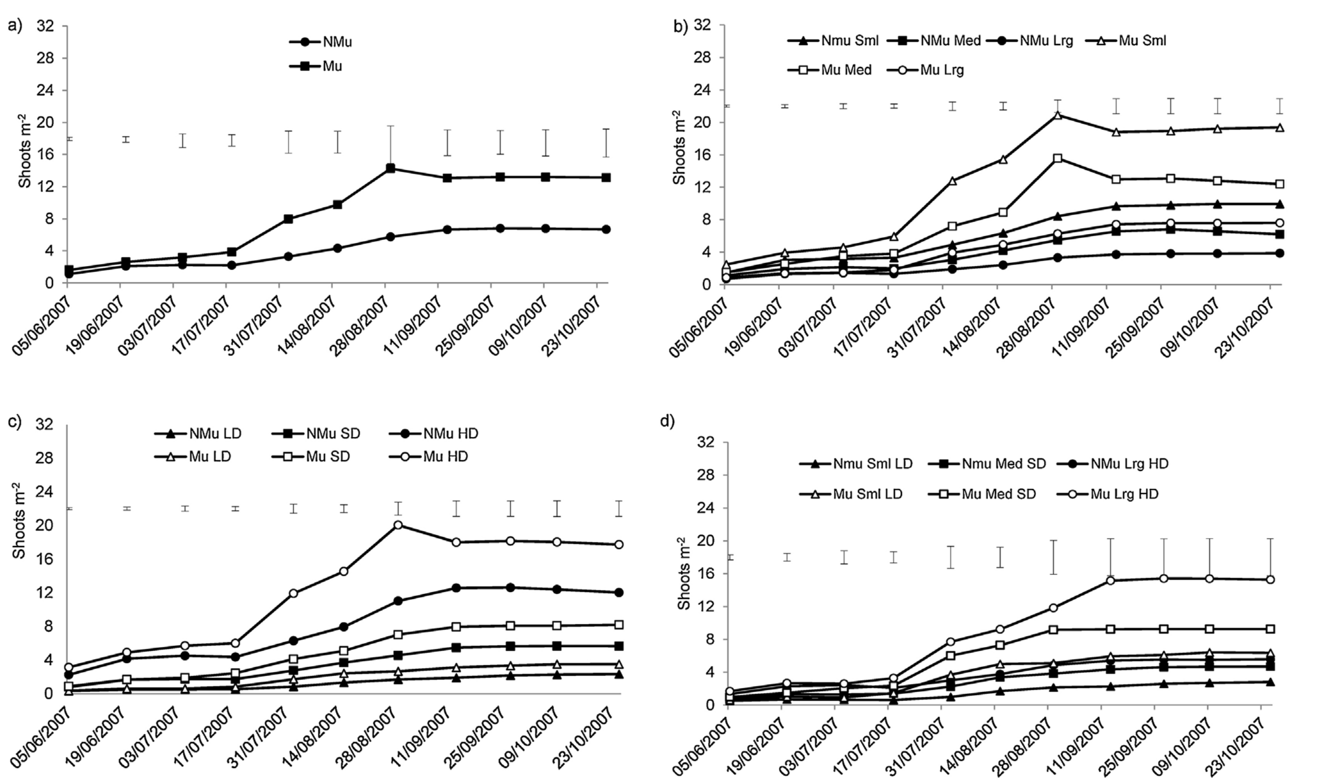

Fig. 4. Shoot population density at intervals at Hillsborough during establishment year for a) mulched and unmulched treatment, b) mulched and unmulched and rhizome size treatments, c) mulched and unmulched and rhizome density treatments and d) treatments planted with the same rhizome number density of 7.2×10^3 rhizomes ha^{-1}. Bars are LSDs.

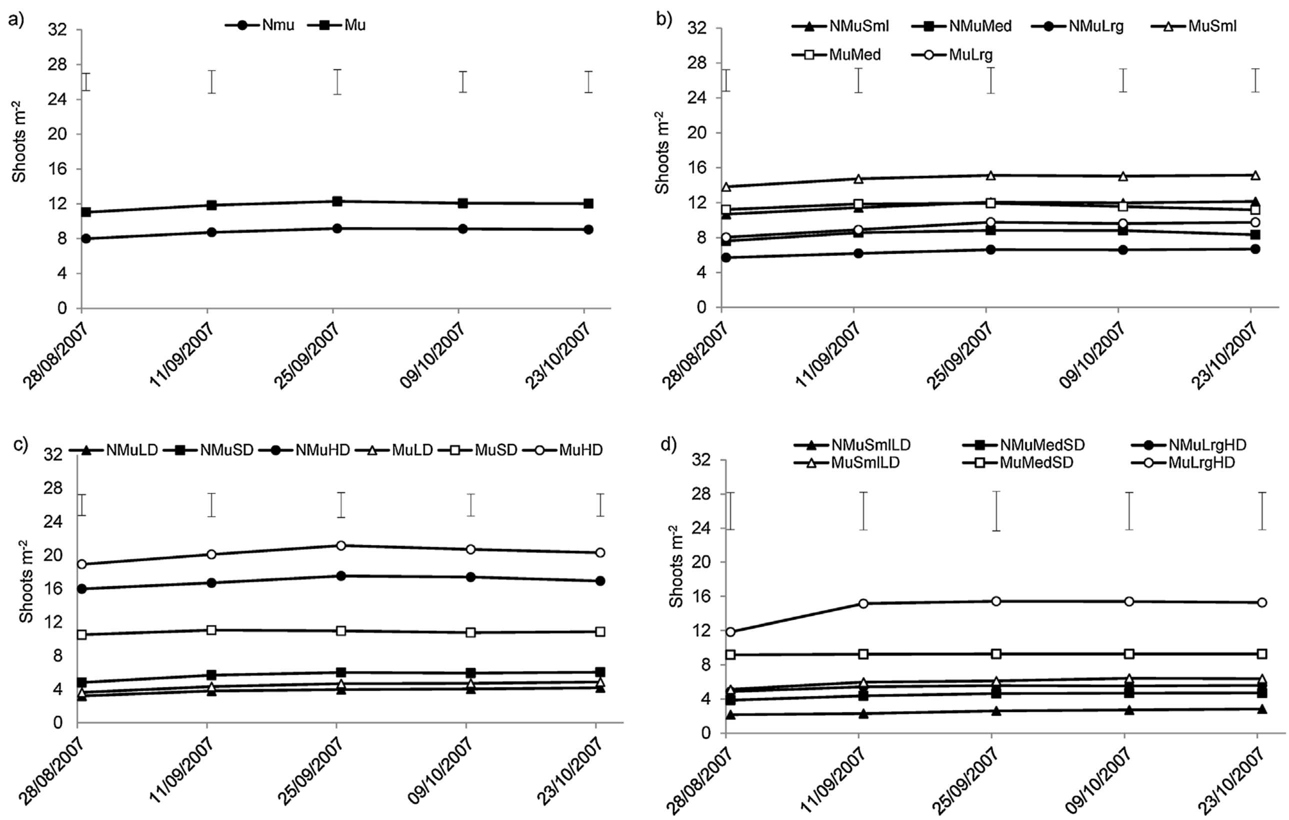

Fig. 5. Shoot population density at intervals at Loughgall during establishment year for a) mulched and unmulched treatment, b) mulched and unmulched and rhizome size treatments, c) mulched and unmulched and rhizome density treatments and d) treatments planted with the same rhizome number density of 7.2×10^3 rhizomes ha^{-1}. Bars are LSDs.

7.2×10^3 ha^{-1} and 21.6×10^3 ha^{-1}) and the largest rhizomes had a positive effect on shoots per plant at 2.4 and 7.2×10^3 ha^{-1}. Also Sml rhizomes produced significantly less shoots per plant than Med rhizomes at 21.6×10^3 ha^{-1}.

At the spring harvests in 2010 mulch had a positive effect at 7.2 and 21.6×10^3 ha^{-1} while size had no significant effect at any of the densities. In spring 2011, mulch had a significant ($P < 0.001$) effect only at 7.2×10^3 ha^{-1} and the largest rhizomes produced significantly ($P < 0.001$) more shoots per plant at 2.4×10^3 ha^{-1} rhizome number density.

3.5. Mineral content

Whole shoots were analysed for N, P and K contents in 2008 and 2011. Mulch had no effect on N, P or K content in any year (Table 8). For the three elements from 2008 to 2011. Responses to rhizome size or density were not consistent over years. In 2008, as density increased N content declined, P declined significantly at the highest density and K content declined from LD to SD. In 2011 nitrogen content was significantly higher at HD than at the other two densities and potassium content increased with increasing density while potassium content declined with increasing rhizome size from Med to Lrg.

3.6. Offtake

Generally, offtakes for each element for treatments within the one year were in proportion to biomass yields as contents did not vary as widely as biomass yields (Table 9). Offtakes for all three elements were higher for the mulch treatment in both years that offtake was measured. In 2008, the effect of mulch on N, P and K offtake in harvested biomass at each of the sites increased with rhizome density (Table 9). Although the proportionate increase in offtake due to mulch treatment was broadly independent of rate of offtake without mulching, for the low density treatment the arithmetic increase due to mulching was only about one sixth of that for the high density treatment for the three elements.

4. Discussion

Over the four years of this study, the mean monthly air temperature of the first month each year that exceeded the threshold temperature of 6 °C for miscanthus to grow (Caslin et al., 2015) was April with an average of 8.9 °C. Mean soil temperature during establishment under mulch was estimated to be 6.5 °C higher than unmulched plots

over the 6 month growing season, i.e. in the first year. The plastic mulch gradually deteriorated over the establishment year and first full harvest year, so its effect on soil temperature would have been more marked during establishment. In the establishment year at the Hillsborough site during the period of greatest soil moisture deficit i.e. the two months after planting (Table 2), the effect of mulch on shoot number was relatively small compared with later in the season when soil moisture was less likely to have had an impact. Further, if soil moisture had been a limitation during establishment, rhizome viability would have been expected to be adversely affected (Mann et al., 2013) and alleviated by mulching. However, viability was high and mulching had no effect. Therefore, the benefit of mulch was more likely to have been due to elevation in soil temperature rather than preservation of soil moisture under the conditions at the site. In the first winter of the trial conditions were relatively mild with minimum air temperatures for all of the winter months remaining above 0 °C, it is assumed that plants living in autumn 2007 were alive in spring 2008.

Due to the definition of density adopted, i.e. kg fresh weight of rhizome planted ha^{-1}, inevitably for a given rhizome density the planting rate (number of rhizomes planted ha^{-1}) of the larger rhizomes was lower for the large than the smaller rhizomes. In fact, due to the design of the experiment the Med rhizomes were planted at one third

Table 4
Mean biomass (t ha^{-1}) for main treatments with harvested in spring at both sites for years 2008–2011.

Variable	Biomass (t ha^{-1}) harvested in spring			
	2008	2009	2010	2011
Mulch				
NMu	0.47	4.79	7.74	8.12
Mu	0.79	7.15	10.55	10.06
Sig	***	**	**	**
LSD	0.140	1.570	1.309	0.917
Rhizome size				
Small	0.81^{a}	7.59^{a}	11.75^{a}	12.13^{a}
Medium	0.65^{b}	6.53^{a}	10.08^{b}	8.96^{b}
Large	0.43^{c}	3.81^{b}	5.60^{c}	6.18^{c}
Sig	***	***	***	***
LSD	0.151	1.533	1.318	1.139
Rhizome density				
LD	0.18^{c}		3.96^{c}	5.12^{c}
SD	0.43^{a}	3.70^{b}	9.28^{b}	9.48^{b}
HD	1.27^{b}	8.25^{a}	14.19^{a}	12.66^{a}
Sig	***	***	***	***
LSD	0.151	1.251	1.318	1.139
Mulch x Rhizome size				
Sig	ns	*	ns	ns
LSD	0.213	2.236	1.903	1.533
Mulch x Rhizome density				
Sig	**	*	ns	ns
LSD	0.213	1.889	1.903	1.553
Mulch x Rhizome size x Rhizome density				
Sig	ns	ns	*	**
LSD	0.368	3.094	3.235	2.738

Means in the same column for a given variable followed by different superscripts are significantly different. LSD = least significant difference; ns = not significant, * = P < 0.05, ** = P < 0.01, *** = P < 0.001.

Table 6
Mean shoot weight (g DM) at spring harvests 2009–2011 and shoot population density for spring harvests 2010 and 2011 for both sites.

Variable	Shoot weight (g)			Shoot population density (m^{-2})	
	2009	2010	2011	2010	2011
Mulch					
NMu	26.6	37.3	35.9	20.6	22.5
Mu	30.4	40.4	35.6	25.3	27.9
Sig	ns	ns	ns	***	**
LSD	4.41	4.87	3.08	1.92	2.12
Rhizome size					
Small	28.1	36.3^{b}	36.7	31.1^{a}	34.4^{a}
Medium	28.4	39.5^{ab}	36.2	24.7^{b}	24.3^{b}
Large	29.0	40.7^{a}	34.4	13.1^{c}	16.8^{c}
Sig	ns	*	ns	***	***
LSD	3.15	3.53	2.07	2.76	2.89
Rhizome density					
LD		34.4^{b}	34.0^{b}	11.5^{c}	15.0^{c}
SD	25.3	40.5^{a}	36.0^{ab}	22.7^{b}	26.4^{b}
HD	31.7	41.6^{a}	37.3^{a}	34.7^{a}	34.1^{a}
Sig	***	***	**	***	***
LSD	2.57	3.53	2.07	2.76	2.89
Mulch x Rhizome size					
Sig	***	ns	ns	ns	ns
LSD	5.37	5.98	3.67	3.58	3.80
Mulch x Rhizome density					
Sig	***	ns	ns	**	*
LSD	4.83	5.98	3.67	3.58	3.80
Mulch x Rhizome size x Rhizome density					
Sig	ns	ns	ns	ns	ns
LSD	6.88	9.14	5.45	6.56	6.91

Means in the same column for a given variable followed by different superscripts are significantly different. LSD = least significant difference; ns = not significant, * = P < 0.05, ** = P < 0.01, *** = P < 0.001.

the rate of the small Sml and the large Lrg were planted at one third the planting rate of the medium. Therefore, in instances when means between rhizome size treatments were significantly different, the number of rhizomes planted also need to be taken into account when interpreting these differences. The data in Table 7 reinterpret density in terms of rhizome number per ha.

The sampling area was 2.7% of the total plot area for all treatments except those planted at 6 and 18 rhizomes per plot, when one third of the plants were sampled (33% of the plot). Precision of the experiment was sufficiently high to identify significant differences in biomass between main treatments of 1.3 t ha^{-1}, averaged over the three harvests after establishment. Maximum biomass yield at each site in each year increased until the third harvest year (2010) and Clifton-Brown et al. (2000) have calculated by modelling and application of GIS that the potential yield at the end of the growing season should be in the range 18–20 t DM ha^{-1}. Allowing for a DM loss of 3 t DM ha^{-1} over winter (Amougou et al., 2011; Finnan and Burke, 2014) potential spring harvestable yields are in the range 15–17 t DM ha^{-1}. The recommended planting rate of rhizomes is approximately between 16,000 and 20,000 ha^{-1} (Atkinson, 2009; Caslin et al., 2015) and the range in this study encompassed this rate i.e. in treatments MedHD and SmlSD, planted at 21,600 rhizomes ha^{-1}. The DM yields in 2010 and 2011 broadly support the recommended planting rate.

The herbicide treatments were effective and so young developing shoots did not encounter competition from weeds. The adverse effect of small rhizomes on the population density of shoots during establishment, was quantified by comparing the shoot density of small size at

Table 5
Mean biomass (t ha^{-1}) for main treatments with harvested in spring at both sites for years 2010 and 2011 for significant mulch x rhizome size x rhizome density interactions (P < 0.05 in 2010 and P < 0.01 in 2011, see Table 4).

Variable	Biomass (t ha^{-1}) harvested in spring																	
	2010									2011								
	Small			Medium			Large			Small			Medium			Large		
	LD	SD	HD	LD	SD	HD	LD	SD	HD	LD	SD	HD	LD	SD	HD	LD	SD	HD
Mulch																		
NMu	5.04	10.01	14.44	2.59	7.52	15.76	1.27	3.81	9.25	8.77	11.93	12.33	3.98	7.37	12.03	1.90	5.15	9.62
Mu	9.69	16.79	14.57	3.79	12.69	18.15	1.40	4.89	12.98	11.30	14.83	13.64	3.58	12.91	13.87	1.18	4.72	14.49

Table 7
Mean number of shoots per viable rhizome of different sizes in non-mulched and mulched treatments for both sites when the same rhizome number per ha were planted.

Variable	Rhizome planted (,000 ha $^{-1}$)								
	Autum 2007			Spring 2010			Spring 2011		
	2.4	7.2	21.6	2.4	7.2	21.6	2.4	7.2	21.6
Mulch									
NMu	16.2	8.7	5.1	40.7	29.4	18.0	60.1	39.2	17.1
Mu	21.5	16.5	9.2	49.2	46.4	21.2	56.9	59.3	20.8
Sig	ns	***	***	ns	***	**	ns	**	ns
LSD	6.09	3.29	1.74	8.77	7.04	1.74	15.55	11.09	4.18
Rhizome size									
Small		9.1^{b}	6.6		35.6	18.5		52.4	20.5
Medium	16.7	12.0^{b}	8.5	41.7	37.3	20.6	51.1	42.2	17.4
Large	21.0	16.6^{a}		48.1	40.9		65.9	53.1	
Sig	**	***	*	ns	ns	ns	**	ns	ns
LSD	2.66	2.50	1.39	7.53	7.65	3.89	9.67	10.16	4.08
Mulch x Rhizome size									
Sig	ns	**	ns	ns	ns	*	ns	ns	ns
LSD	6.34	4.10	2.07	10.70	10.68	4.11	17.11	15.15	5.42

Means in the same column for a given variable followed by different superscripts are significantly different. LSD = least significant difference; ns = not significant, * = P < 0.05, ** = P < 0.01, *** = P < 0.001.

Table 8
Effect of plastic mulch and size and density of rhizomes planted on nitrogen (N), phosphorus (P) and potassium (K) content (g kg^{-1}) in whole shoots of miscanthus harvested in spring in selected years.

Variable	Nutrient content (g kg^{-1})					
	N		P		K	
	2008	2011	2008	2011	2008	2011
Mulch						
NMu	10.50	3.36	1.44	0.62	13.80	5.90
Mu	11.20	3.35	1.39	0.64	15.00	5.96
Sig	ns	ns	ns	ns	ns	ns
LSD	0.981	0.395	0.175	0.162	1.202	0.699
Rhizome size						
Small	11.00	3.38	1.47	0.68	14.20	6.48^{a}
Medium	11.00	3.38	1.41	0.62	14.70	6.30^{a}
Large	10.40	3.31	1.37	0.60	14.30	5.02^{b}
Sig	ns	ns	ns	ns	ns	***
LSD	0.643	0.240	0.092	0.069	0.822	0.402
Rhizome density						
LD	11.60^{a}	3.28^{b}	1.48^{a}	0.61	15.00^{a}	4.68^{c}
SD	10.80^{b}	3.16^{b}	1.45^{a}	0.63	13.80^{b}	5.81^{b}
HD	10.00^{c}	3.62^{a}	1.32^{b}	0.66	14.50^{ab}	7.30^{a}
Sig	***	***	**	ns	*	***
LSD	0.643	0.240	0.092	0.069	0.822	0.402

Means in the same column for a given variable followed by different superscripts are significantly different. LSD = least significant difference; ns = not significant, * = P < 0.05, ** = P < 0.01, *** = P < 0.001.

low density, medium size at standard density and large size at high density. This is corroborated in the established crop where the largest rhizomes produced the highest number of shoots per plant at some densities in two of the three years that it was measured (Table 7). Although not tested statistically, the general trend was that the more densely planted the rhizomes the less were the number of tillers per plant. Hocking et al. (2008), Pyter et al. (2010) and Khan et al. (2011) have also found that small rhizomes produce fewer shoots than larger rhizomes.

The effect of mulch during establishment was to approximately double shoot population density by autumn. This was reflected in

Table 9
Mean offtake of N, P and K (kg ha^{-1}) at spring harvests in two years for unmulched and mulched miscanthus, averaged over two sites.

Variable	Offtake (kg ha^{-1})					
	N		P		K	
	2008	2011	2008	2011	2008	2011
Mulch						
NMu	4.42	27.80	0.62	5.21	6.10	55.50
Mu	8.48	34.40	1.02	6.75	12.11	69.70
Sig	***	*	**	*	**	ns
LSD	1.384	5.830	0.197	1.293	2.956	14.430
Mulch x Rhizome density						
Sig	***		**		**	
LSD	2.175		0.293		4.212	

LSD = least significant difference; ns = not significant, * = P < 0.05, ** = P < 0.01, *** = P < 0.001.

harvested DM yield in spring in 2008. This suggests that winter survival was not affected by mulch and the winter of 2007-8 was the mildest of the four during the experiment. Although proportionately less at successive spring harvests, higher biomass yield due to mulch persisted to the end of the experiment, even although its direct effect would have been greatly diminished by the end of the first full harvest year due to breakdown of the mulch. This demonstrates the importance of achieving a high shoot density during establishment to provide a basis for high miscanthus biomass yield at spring harvests in subsequent years.

The components of above-ground biomass yield of miscanthus are shoot DM weight and shoot population density. The impact of rhizome size planted on shoot weight did not follow a consistent pattern but shoots in stands at the lowest planting density were often lighter than in the more dense treatments. This is counter to the concept of self thinning in which as a consequence of development of a dense stand, the size of the units decreases (e.g. Kays and Harper, 1974), sometimes referred to as ‘size density compensation’. The effect of mulch on shoot weight at the spring harvest was not consistent, although a slight positive trend was suggested. However, reduction in shoot number per planted rhizome with increase in density would be consistent with the increase in aerial competition between plants as plant density increases.

As already discussed, the effect of rhizome size on shoot population density was misleading without interpretation. However, irrespective of rhizome size planted, there were strong indications that with time, shoot densities that had been initially low gradually approached corresponding initial higher densities. Kilpatrick et al. (1994) found that by reducing planting densities from 4 to 1 m^{-2}, number of stems per plant increased relative to the higher density treatment. So although planting rate of the low density treatment was only one quarter that of the high density treatment, it produced half of the yield. Within limits, initial contrasting planting rates will eventually result in similar equilibrium shoot population densities (Bullard et al., 1997). In this study, despite higher yields due to mulching being maintained in the fourth harvest year, the effect of mulch on the component of yield most responsible for the difference i.e. shoots per plant, declined with time, especially in the low density treatments.

No fertiliser was applied to the crop during the experiment. Compared to the analysis of studies embracing 60 observations of N concentration of miscanthus crops harvested in the winter, in the review of Cadoux et al. (2012), the mean N concentration in this study for 2008 was well in excess of the third quartile while that for 2011 was only slightly above the first quartile. The trial was planted in cultivated long term grassland and so the rate of soil N mineralisation would have been high, at least 60 kg N ha^{-1} annum^{-1} (DEFRA, 2010). Despite that and the potential for miscanthus, in association with diazotrophic endophytic bacteria to fix atmospheric nitrogen (Keymer and Kent, 2014) the N content in overwintered miscanthus declined over the three years from a relatively high level to below the median for the group of recorded studies. The mean concentration of P and K in the 2011 harvest was above and slightly below the median for the reviewed concentrations, respectively (Cadoux et al., 2012).

Mulching did not have a significant effect on concentration of N, P or K in harvested biomass. In a preliminary assessment of change in rhizome biomass over the three winters in this study in only one treatment, 40–50 kg K ha^{-1} were estimated to have been remobilised to the rhizomes and roots per year, based on total accumulation in these organs over the experiment. Kahle et al. (2001) found that available K increased under miscanthus, which they attributed to recycled K in senescent material in litter, especially leaves and stem tips. In this study K offtake in spring harvest was 116 kg K ha^{-1} less than in the previous autumn meaned over the six highest yielding treatments. Nutrients are remobilised in autumn and early winter from aerial parts to rhizomes and roots in miscanthus (Christian et al., 1997; Beale and Long, 1997; Strullu et al., 2011).

4.1. Application

If biomass yields in the third and fourth spring harvests are considered to reflect the long term effects of mulch, it can be concluded that mulch had a benefit both on increasing the ceiling yield in some instances or, more consistently, reducing the required rhizome size and/or density to achieve a given long term yield. This effect was seen especially for planting rhizome density of 7.2×10^3 ha^{-1}.

Evaluating the economic feasibility of using mulch on miscanthus can be considered either in terms of increase in biomass that can result from using mulch or, alternatively, reducing the planting density of rhizomes but maintaining the same biomass yield. In this trial over four years, mulch resulted in increased production of 7.4 t ha^{-1} (Table 4), equivalent to additional revenue of €481 assuming a price of €65/tonne (Caslin et al., 2015). From Table 5 with the exception of MedLD in 2010 harvest without mulch producing high biomass yield, all treatments which had been planted at 7200 rhizomes ha^{-1} with mulch produced biomass yield similar to 21,600 rhizomes ha^{-1} without mulch. The treatment MedLD without mulch produced 3.1 t ha^{-1} in 2010 more than MedSD with mulch. The cost of mulch is approximately €380 ha^{-1} (Dr Eamonn Meehan, AFBI Maize Forage Scientist 2016, personal communication) and the cost of a rhizome is approximately 8.4 cents (Caslin et al., 2015). Therefore reducing planting density from 21,600 to 7200 ha^{-1} and applying mulch results in a saving of €1339 ha^{-1}. However if account is taken of a shortfall of 3 t ha^{-1} in one year valued at €60 t^{-1} the net saving due to mulch is €1159 ha^{-1}.

5. Conclusions

The benefit of mulch was to increase the rate of establishment of miscanthus through increasing the rate of shoot production per plant and thereafter to increase the rate at which stands grown from smaller or less densely planted rhizomes than recommended approach their ceiling yields. While some of these mulched treatments had reached their ceiling yield within the four annual harvests of this experiment, the experiment was terminated too early to determine if this would be achieved in others.

Over all treatments in the four spring harvests in this experiment, plastic mulch resulted in an average increase in biomass yield of over 30%. Also in the last two years that biomass from small rhizomes was measured the lower planting rate with mulch produced a total of 3.6 t ha^{-1} less than the higher rate. So the cost of laying the mulch, rhizome size and planting density have to be offset against this benefit; however, the additional cost of mulch for routine planting operations would be justified. Further, results from an associated study on the calorific value and other combustion characteristics of miscanthus (Easson et al., 2011) need to be taken into account when assessing the economic feasibility in the use of mulch in the management of miscanthus. Nevertheless the results of this study suggest that under the cool temperate conditions of Northern Ireland covering planted rhizomes with plastic mulch has potential to be an effective management practice to establish miscanthus for biomass production.

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