Investigating the longterm biomass yield of Miscanthus giganteus and switchgrass when harvested as a green energy feedstock

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INVESTIGATING THE LONGTERM BIOMASS YIELD OF MISCANTHUS GIGANTEUS AND SWITCHGRASS WHEN HARVESTED AS A GREEN ENERGY FEEDSTOCK

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ABSTRACT: Recent research has indicated that the leading perennial energy grasses, *Miscanthus giganteus* and switchgrass (*Panicum virgatum*) may be utilized for non-thermal energy conversion. The feedstock requirements for these conversion technologies would allow the crops to be harvested early, prior to senescence, to exploit the greater higher biomass yields that occur during the autumn. Miscanthus grown at three locations in Europe was continually harvested early and maintained its high peak yield when compared to the conventional spring post-senescence yield. At one site, where the crop was continually harvested for 6 years, the early harvest yield began to decline after four years although this yield decline did not occur when the crop was adequately supplied with additional nitrogen. The two ecoptypes of switchgrass grown at locations in Europe, responded very differently to an early harvest. Lowland switchgrass at two locations could not maintain the high peak yield even with a moderate application of nitrogen. Upland switchgrass examined at one location did sustain high peak yields for 5 years of continuous early harvest without the need for additional nitrogen. The results of this study have indicated that a continual early harvest of both miscanthus and switchgrass is possible but replacement plant nutrients must be applied to the crop to revent or limit the extent of any yield decline.
Keywords: Yield, Miscanthus, Switchgrass, Fertilisation.

1 INTRODUCTION

The perennial energy grasses, miscanthus and switchgrass (Panicum virgatum) are two of the leading biomass feedstock's that are currently being commercially utilised in Europe and the US. Switchgrass was identified by the US in the early nineties as the model dedicated energy crop [1] whilst Miscanthus, a C4 perennial rhizomatous grass, has been extensively investigated as a possible raw material for energy for many years [2]. Both grasses possess numerous favourable energy crop characteristics; the C4 pathway which will allow an enhanced carbon fixation rate and a high water efficiency and a rhizome which can provide an overwinter reservoir for nutrients that can be utilised the following spring.

The current use of these feedstock's for bioenergy has typically focused on thermal conversion such as combustion and gasification. However, recent research has suggested that these grasses will be an excellent feedstock for non-thermal conversion including ligncellulosic biorefining [3] and anaerobic digestion [4]. The feedstock quality requirements for thermal conversion are very different to that of a non-thermal feedstock. For thermal conversion, the moisture content of the feedstock must be as low as possible (<18%) and contain low levels of possible boiler contaminants (potassium, chloride and nitrogen). Non thermal conversion pathways do not have such limitations and a low moisture content is not an important yield determinant in most hydrolysis biorefining technologies [5]

Conventional harvesting of the energy grasses occurs during winter (late winter early spring in the UK), after the crop has fully senesced and nutrients have been remobilised into the rhizome. This late harvest reduces above-ground crop moisture and by extending the harvest period further, the contaminant composition of the feedstock is lowered through natural weathering processes. [6] reported biomass N P and K concentration in winter to be 61%, 64% and 55% of that in autumn in miscanthus thus increasing thermal feedstock quality. Additionally, by delaying the harvest, the crop can also remobilise and recycle nutrient for the following year's growth. Perennial plants use nitrogen reserves/ rhizome for regrowth in spring and the amount of remobilised nitrogen is dependent on nitrogen stocks before regrowth for *M giganteus* [7]. In switchgrass, delaying the harvest until the end of the growing season or after a killing frost can significantly reduce nutrient requirements and improve switchgrass stand longevity [8].

However, the maximum biomass yield of both the upland switchgrass and miscanthus occurs during the summer months, during flowering or just prior to senescence. Extending the harvest window and harvesting in late winter will reduce the dry matter yield of the crop. [9] estimated that miscanthus and upland switchgrass can lose 31.1 kg ha^{-1} day^{-1} and 21.3kg ha^{-1} day^{-1} of dry matter respectively between the period of maximum biomass and conventional crop harvest date in the UK. This overwinter loss in miscanthus was also presented by [10] who estimated that in northern France, there was a 28-30% decline in dry matter yield when the crops were harvested after winter.

The autumn/green harvesting of energy grasses was considered as the most efficient way of utilising biomass. An autumn harvest will potentially achieve the highest possible yield per unit of land for miscanthus and upland switchgrass. Unfortunately, there has been very little research into consequence of these harvests on the future growth of the crop. Removal of the crop before senescence and nutrient remobilisation, will remove vital plant nutrients from the field which will need to be replaced through the application of fertilisers. [7] suggested that miscanthus harvested too early in the autumn might not be able to translocate its nutrients to its rhizomes and a higher fertilisation will be needed. However, in miscanthus the sustainability of an autumn harvest has yet to be assessed over a long period [4]. In upland switchgrass, [11] found that a mid-August harvest in north central USA reduced stand density over time which is similar to observations made in Pennsylvania [12]

Exploiting the higher autumn yields of miscanthus and switchgrass for future non-thermal energy conversion technologies will increase energy yields per unit area. This may not be due to the evolution of their composition for each technology but it is simply due to the high yields that autumn harvests offer [10]. This study which is part of the EU funded LogistEC project, will present preliminary results from several experiments across Europe that will compare early and late harvest yields in miscanthus and switchgrass. The study will include yield data from *Miscanthus giganteus* and several genotypes and ecotypes of switchgrass. As previous researchers have suggested, the effect of nitrogen fertiliser on both autumn and winter yields will also be examined.

2 MATERIALS AND METHODS

2.1 Field experiments

The field experiments were conducted at four locations in Europe UK, France and Italy and are presented in table I.

Table I: The location and crop and planting dates of all field experiments

Country	Location	Crop	Genotype
France INRA	Estree-Mons	*M giganteus*	-
		Switchgrass	Kanlow
UK RRES	Woburn, Beds	*M giganteus*	-
	Rothamsted, Herts.	Switchgrass	Cave in rock
	Rothamsted, Herts.	Switchgrass	Pangburn
Italy SSSA	Pisa	*M giganteus*	-

INRA, Estrées -Mons, France

The field experiment was established in 2006 at the INRA experimental station in Estrées-Mons, northern France (49.872°N, 3.013°E). The soil is a Haplic Luvisol (IUSS Working Group WRB, 2006). Over the period 2006-2012, the mean annual temperature was 10.6 °C and annual rainfall and potential evapotranspiration were 680 and 729 mm respectively. Before 2006, the field had been cultivated for many years with annual crops and the previous crop was winter wheat following spring pea.

After winter wheat harvest in 2005, the field was mouldboard ploughed in early December and left bare during winter. Miscanthus was planted in April 2006 (1.5 rhizome m^{-2}) and switchgrass sown in June 2006 (seed rate = 15 kg ha^{-1}). The crops were not harvested nor fertilised during the first year but the aboveground biomass was chopped in January 2007 and left on the soil surface. From 2007 onwards, the N fertiliser was applied as UAN solution (urea ammonium nitrate) in N+ treatments, with a single annual application in late April . The experiment did not receive irrigation.

Since 2007, the crops are harvested either early in October (E) or late in February (L). The experiment also includes two nitrogen treatments: unfertilised (N-) and fertilised with 120 kg N ha^{-1} yr^{-1} (N+). It is a split-block design (three replicate blocks) with "crops" in the main plots (miscanthus E, miscanthus L, switchgrass E, switchgrass L) and N fertilisation rates in the subplots (N- and N+). Subplots are 360 m^2

Rothamsted Research, Woburn experimental farm, UK (Miscanthus)

The miscanthus experiment was conducted at the Woburn Experimental farm in Bedfordshire, UK (52 01^o N, 00 36 W), *ca* 100m AOD. In 2003 rhizomes of *Miscanthus* x *giganteus* were lifted from an existing site, graded by hand and planted into an area of approx. 1ha (3.5 rhizome/m^2). The soils are described as approximately equal areas of Cottenham and Stackyard Series [13]. Soil P was considered adequate for plant growth and N K and S fertiliser were not applied during the initial year.

The field was used for several research experiments and during 2009 and 2010 some plots were cut early as part of a larger storage experiment. During 2011 and 2012, the field was fertilised annually with 100kg N ha^{-1} and harvested in April. Treatments were added to the experiment to measure any residual effects from previous cropping. These treatments indicated that previous experiments had not affected the crop and experiment and were therefore omitted from this paper.

The experiment consisted of a fully replicated block design with 4 different treatments, Early harvest (October) with annual application of 50kg N ha^{-1} and without nitrogen. Late harvest (May) with an annual application of 50kg N ha applied and without nitrogen. Each plot was 6m x 35m. The experiment received an annual application of 100kg of Nitrogen and 50kg of Potassium in May, 2013 and 2014. The nitrogen experimental treatments were applied in 2014.

Rothamsted Research, UK (Switchgrass)

The experiment was established at Rothamsted Research in south east England (latitude 51^{o}48'30" N longitude 0^{o}21'10" W, altitude 128m OD) in 1998. The soil is a moderately well-drained flinty, silty, clay loam over clay-with-flints [11]. The switchgrass seed (Pangburn and Cave-in-rock) was sown in June 1998 into a fine seed bed using an Oyjord precision drill, at a rate of 500 live seeds m^{-2}. Potassium and phosphorous fertilizers were incorporated into the seed bed before drilling at a rate of 95kg K ha^{-1} and 50kg P ha^{-1}. Nitrogen fertilizer was not applied in the establishment year as crop growth was expected to be slow, and excess nitrogen would promote weed growth. The initial experiment was a randomised block design with 4 genotypes and nitrogen treatments. Pangburn with an annual application of 75kg N ha N and without nitrogen Cave-in-rock with an annual application of 75kg N ha N and without nitrogen. These 5m x 8m plots were split into early harvest and late harvest plots (2.5m x 8m)in 2003 and harvested in autumn (early harvest) and late winter (late harvest). In 2008, all plots were harvested in late winter.

SSSA, CIRAA, Pisa, Italy

The experiment was carried out by the Institute of Life Sciences of Scuola Superiore San'Anna at the Interdepartmental Centre for Agro-Ecological Research (CIRAA) in the Pisa coastal plain (central Italy; latitude

43°680 N, longitude 10°350 E; 1 m a.s.l. and 0% slope) from 2010 to 2013.

The area, having originated from land reclamation, is characterized by heterogeneous soil textures, with different soils located within few hundred meters one another, and thus provides a particularly suited site for comparing soil effects under the same environmental conditions (e.g., meteorological conditions, water table depth, etc.).

In spring 2010, two adjacent fields characterized by two contrasting soil textures, i.e. silty-clay-loam (SiC) and sandy-loam (SL), were used to carry out the following experiment: three main plots were arranged in the SiC soil and three in the SL soil. Within each main plot, three nitrogen fertilization levels [0 (N0), 50 (N50), 100 (N100) kg h^{-1}] were randomly assigned as subplots (size 6.5 x 5.0 m).

The soil was a Typic Xerofluvent, representative of the lower Arno river plain, characterized by a shallow water table never below a 2.5 m depth even during the driest period.

Tillage was conducted in the autumn of 2009: ploughing, followed by rotary harrowing immediately before planting. Crop establishment occurred on on April 22, 2010 using rhizomes, at a density of two plants per m^2 (1 x 0.5 m spacing). No preplant fertilizer was required. Plants were watered throughout the first growing season to get them established. By the end of the first year, the establishment rate was close to 100% in all plots. Weeding and pest control were never necessary at any point during the trial.

Nitrogen (urea) fertilization was always applied in the spring, when crops were 0.20–0.30 m tall.

2.2 Measurements

INRA. Miscanthus

Harvested crop production was measured every year from 2007 to 2012. On each harvest date, the aboveground biomass was collected manually in one micro-plot inside each plot. The size of the micro-plot was 3.84 m^2 for miscanthus (six plants) and 2.5 m^2 for switchgrass. The cutting height was 7 cm. The fresh biomass was weighted and a representative subsample was dried at 65 °C for 96 h to determine the dry matter content. In order to better take into account canopy variability of miscanthus, the measured biomass was corrected by the number of stems determined in a wider undisturbed area of 25 m^2 according to Strullu *et al.* (2011).

RRES Miscanthus.

The crop was harvested using a reed yield cutter (cutter bar width 1.42). One length of approximately 35m x 1.42m (measured accurately after harvesting) of crop was cut using the reed cutter with all material being collected and weighed. A sample of the harvested material was collected from each plot and dried at 80°C for 36 hours to calculated moisture content and dry matter.

RRES Switchgrass

The crop was harvested using a modified reed cutter (cutter bar width 1.42).Prior to the measurements a small border area of 50cm was taken from the edge of each plot to eliminate edge effects. Using the reed cutter, a 1.42m strip from each subplot was cut and the crop was weighed and a sample taken. This sample was dried at 80°C for 36 hours crop to allow moisture content and dry matter to be calculated.

SSSA Miscanthus

Each year, with exception of 2010, the establishment year, productive measurements were collected in two different periods: early autumn, at flowering stage (FS) (i.e. mid October), and winter (W) (i.e. end of January – early February). Harvest time was assigned as sub-sub-plots within each fertilization level.

At each harvest time, the aboveground biomass yield (AGBY_FS and AGBY_W) was sampled in a 4 m2 area (2 x 2 m^2) and fresh weight was determined. Border plants from the outer rows were not included in the sampling area. Plant subsamples were partitioned into leaves, stems and inflorescence. After partitioning subsamples were dried at 60 °C until constant weight to determine the dry matter content and dry biomass yield. Aboveground dry yield was derived as the sum of leaves, stems and inflorescence components.

3 RESULTS

3.1 Miscanthus

The annual dry matter yields taken from the early and late harvested plots at INRA are presented in figure 1 (with nitrogen) and figure 2 (without nitrogen). Both graphs indicate that the miscanthus grown at INRA does not respond to nitrogen when the crop is harvested late. In the high nitrogen treatment, the late harvested crop has a lower yield than the early harvested crop every year with a 20-30% reduction. Where nitrogen has not been applied the first years show a reduction in yields from early to late harvest but this difference becomes smaller in year years 2009 and 2010. In 2011, the miscanthus harvested late has a higher yield than the early harvested crop.

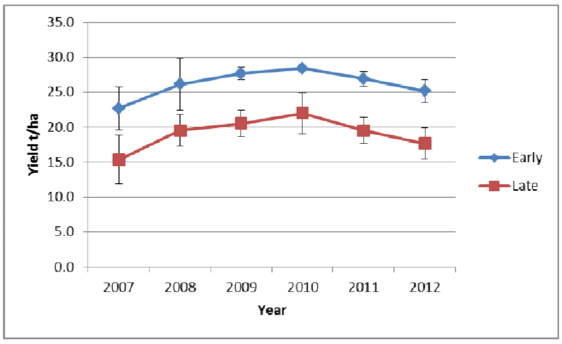

Figure 1: INRA. The annual yield of Miscanthus cut at different harvest dates with 120kg N ha

The miscanthus experiment at RRES has been running for two years and the dry matter yields are presented in figure 3. All of the treatments receive 100kg N ha annually and the additional higher rate of fertilizer has not increased the dry matter yield. There is a 26% and 24% reduction in yield between the early harvest and the late harvest years for both N treatments.

At SSSA where three levels of nitrogen had been applied, the crop responded to the 100kg N ha^{-1} treatment only with an increased yield shown in this treatment at the early and late harvest (figure 4, 5 and 6). The experiment at SSSA is still relatively young with all nitrogen treatments displaying a large reduction in yield from early harvest to late harvest (15-45% reduction)

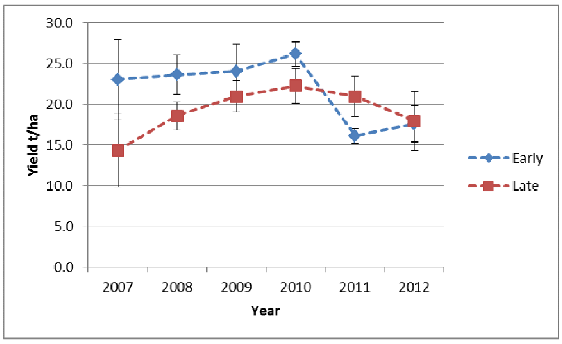

Figure 2: INRA. The annual yields of miscanthus cut at different harvest dates without nitrogen.

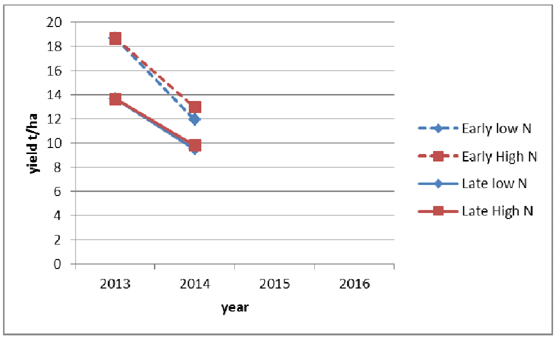

Figure 3: RRES. The annual yield of miscanthus cut at different harvests with two levels of nitrogen fertilizer

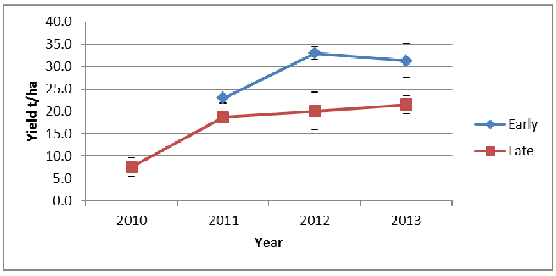

Figure 4: SSSA. The annual yield of miscanthus cut at different harvest dates with 100kg N ha.

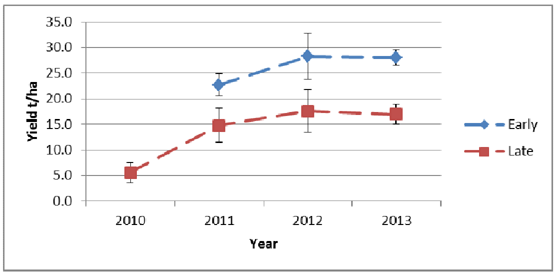

Figure 5: SSSA. The annual yield of miscanthus cut at different harvest dates with 50kg N ha.

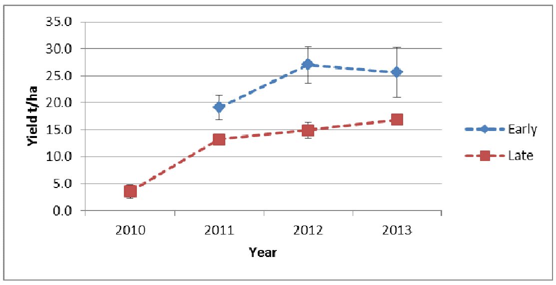

Figure 6: SSSA. The annual yield of miscanthus cut at different harvest dates without nitrogen fertilizer.

All the data from the three locations indicates that there is a reduction in yield from early to late harvest of approximately 30%.

3.2 Switchgrass

The lowland switchgrass grown at INRA did respond to the application of nitrogen (figures 7 and 8). The decrease in yield from early to late harvest is quite small when nitrogen fertilizer is applied (<10%) but in most years the crops did show a reduction in yield from early to late harvest. When nitrogen was not applied, after three years of early cutting, the early harvest yield was lower than the late harvest yield and maintained this reduced yield for the following three years.

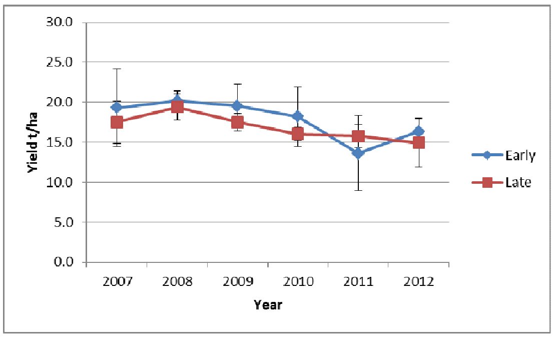

Figure 7: INRA. The annual yield of switchgrass (Kanlow) cut at different harvest dates with 120kg N ha

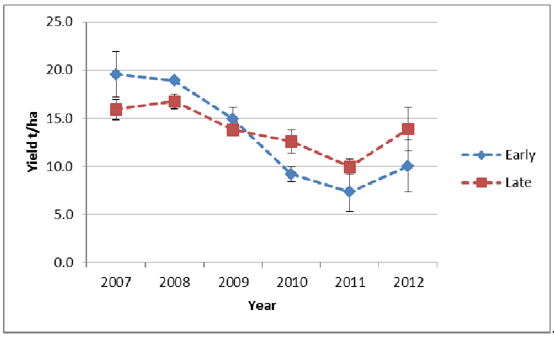

Figure 8: INRA. The annual yield of switchgrass (Kanlow) cut at different harvest dates without nitrogen fertilizer.

The lowland switchgrass, Pangburn, grown at the RRES site did show a slight response to 75kg N ha in some years however this was not a significant response (figure 9 and 10). For the first two years of the experiment there was very little difference in yield between the early and late harvest in either nitrogen treatment. After two years of early harvesting, the yields from the early harvested crop were lower than the late harvest yields, in both nitrogen treatments. However, this difference between the two harvest dates was higher in the crop that had not received nitrogen and this difference increased further each year of the experiment

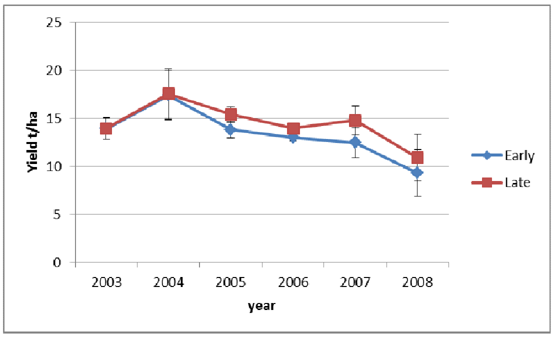

Figure 9: RRES. The annual yield of switchgrass (cv Pangburn) cut at different harvest dates with 75kg N ha

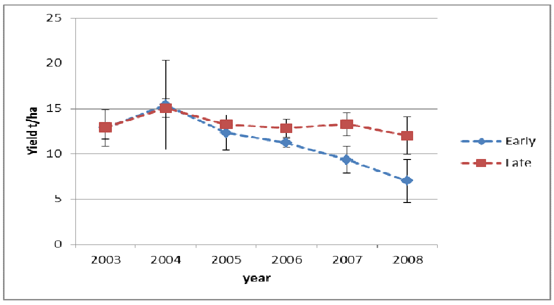

Figure 10: RRES. The annual yield of switchgrass (*cv* Pangburn) cut at different harvest dates without nitrogen.

The yields of RRES upland switchgrass (Cave-in-rock) are presented in Figure 11 and 12. The application of nitrogen did not significantly affect the yields of the switchgrass in either harvesting treatment. For the first 5 years of the experiment there was an approximate 15% reduction in yield from the early harvest to the late harvest and this reduction remain steady throughout. In 2008 however, the early harvest yield fell in the early harvests of both nitrogen treatments.

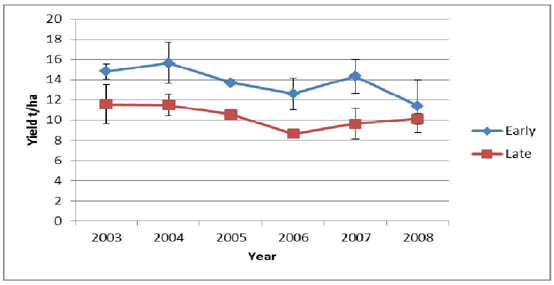

Figure 11: RRES. The annual yield of switchgrass (*cv* Cave-in-rock) cut at different harvest dates with 75kg N ha.

The dry matter yields of the RRES lowland switchgrass (*cv* Pangburn) when the whole experiment was harvested on one date in late winter 2009 are presented in figure 13. The previously early harvested crop yields were considerably lower than the yields taken when the crop was previously harvested late. The application of nitrogen did not affect the yield.

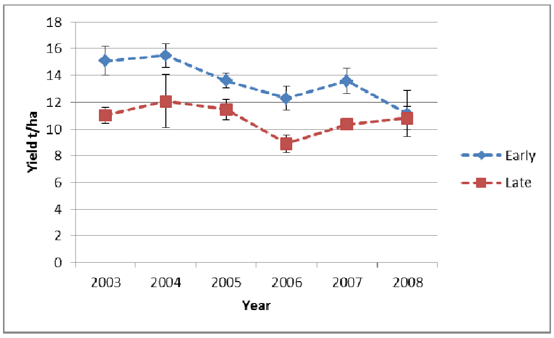

Figure 12: RRES. The annual yield of switchgrass (*cv* Cave-in-rock) cut at different harvest dates without nitrogen.

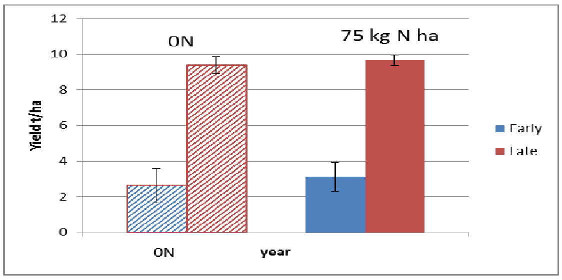

Figure 13. RRES. The yield of switchgrass (*cv* Pangburn) harvest on one date in 2009 after 6 years of early and late harvesting without nitrogen (hatched) and 75kg N ha(bold).

The RRES upland switchgrass dry matter yields again did not respond to the application of nitrogen fertilizer (figure 14.) The yields of the previously early harvested crop were also considerably lower than the previously late harvested crop.

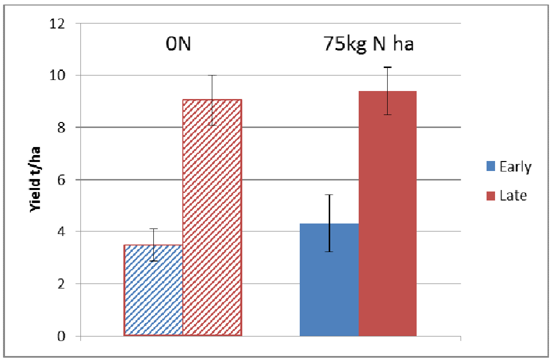

Figure 14: RRES. The yield of switchgrass (*cv* Cave in-rock) harvested on one date in 2009 after 6 years of early and late harvesting without nitrogen (hatched) and 75kg N ha (bold).

4 DISCUSSION

4.1 Miscanthus

The effect of nitrogen on the yield of miscanthus varied greatly in the three locations regardless of harvest date. The miscanthus grown at INRA did not respond to nitrogen fertilizer when conventionally cut although the miscanthus at SSSA responded to nitrogen applied at 100kg N ha. The RRES miscanthus did not respond to the extra nitrogen treatments, however all treatments received a blanket application of 100kg N ha^{-1} as previous experiments had indicated that miscanthus grown on this site did require a moderate application of nitrogen [14]

These results support the studies presented by several researchers indicating that the role of nitrogen in the management and agronomy of miscanthus is still relatively unknown and understanding when and where a crop will respond positively to N is vital [14][15][16]. The early harvested crops did produce a higher yield than the late harvest crop at all locations when the crop had received nitrogen. This is due to not only the over-winter leaf fall but also the carbon translocation from the above ground biomass to the rhizome. In SSSA and RRES, even without nitrogen the early harvest still out yielded the late harvest for the early years of the experiment. At INRA however, the yield of the early harvested crop did start to fall after four years of continuous harvest. As the other locations had yet to reach 4 years of continuous early harvest it is likely that some decline in early harvest yield will be seen in the following years of the experiment at SSSA and RRES

The decline in early harvest yield without nitrogen fertilization over time shown at INRA, has been suggested by several researchers **[7].** Early harvest impedes the complete translocation of nitrogen to below ground rhizomes for use in the following year. Strullu 2011 stated that 71% of the maximum nitrogen content in the above ground biomass was remobilized and stored in late harvested crops whilst only 42% of the nitrogen was remobilized in early harvested crops. This removal of nitrogen from the crop may be replaced by a moderate application of inorganic fertilizer, an application of 120kg N ha^{-1} maintained the early harvest yields at INRA for the last 6 years. The nitrogen could also be replaced by soil mineralization in soils with high organic matter. The early harvest also reduced the transfer of other plant nutrients such as P and K through litter fall [15][16]**.**

Switchgrass

The two distinct ecotypes of switchgrass, lowland and upland behave differently from each other in regards to nitrogen requirements and harvesting management.

At INRA, the lowland ecotype, Kanlow, responded to nitrogen fertilizer and had problems after 3 years, maintaining yields when the crop was continuingly harvested early, without extra nitrogen being applied. However, early harvest responses were also seen with RRES lowland switchgrass yet the crop did not respond to nitrogen in either harvest dates. The RRES lowland switchgrass showed a rapid decline in yield from the early harvested plots after only one year of early harvest regardless of nitrogen application. This reduction in growth in the early harvest was clearly visible when all of the treatments, in 2009, was harvested at one "late" date. These low yields presented in the early harvested Pangburn were irrespective of nitrogen fertilizer application which may indicate that the annual application of 75kg N ha^{-1} may not be sufficient to replace the nitrogen lost from the plant.

The upland ecotype planted at RRES did not respond to nitrogen fertilizer and yield was not affected by early harvesting for the first 5 years. The early harvest had a greater biomass yield than the late harvest in these years which follows the results presented by [9]. In 2008 however, the early harvest yield dropped in both nitrogen treatments. This decline continued in the following years growth and was significantly reduced and visible in 2009 when all the treatments were harvested on the same "late" harvest date. The application of nitrogen made very little difference to this decline in yield indicating that other nutrients may have also been depleted and that the annual application of 75kg N ha may not be sufficient to replace the cumulative nitrogen lost from the plant in the long-term.

The latitude of origin and ecotypes has a large impact on switchgrass yield potential [17]. Lowland ecotypes have a higher yield potential than the more northern upland ecotypes as they do not flower in the northern European climate. The lowland switchgrasses remain in their fully vegetative state throughout the growing season enabling all resources to be focused on vegetative growth. Upland ecotypes will flower in northern Europe, with the time of flowering dependent on the latitude of origin. Flowering in switchgrass halts the vegetative growth prematurely in the growing season thus reducing biomass yields. However the flowering of the crop does induce senesce and nutrient remobilization in switchgrass. In switchgrass, nitrogen is translocated to crown and root tissues as the plant approaches senescence or after a killing frost [8] The nitrogen content of switchgrass cut at peak yield, prior to senescence, is higher than when the crop is harvested after senescence or a killing frost [18]**.**

Harvesting both ecotypes early will remove vital plant nitrogen from the plant system and stop the full remobilization of nitrogen to the crown and rhizome of the switchgrass. However in upland ecotypes, some remobilization will have started to occur as the crop was cut at flowering, just prior to senescence. In lowland switchgrass there would have been very little translocation of nutrients to the rhizomes when the crop is cut early. Harvesting lowland switchgrass after a killing frost (late harvest) will allow remobilization of nitrogen and other plant nutrients to the plant crown and rhizome. An early harvest of lowland switchgrass will rapidly reduce yield of the crop due to the lack of any remobilization of plant nutrients back to the rhizome. The absence of a yield response to nitrogen in both ecotypes during this harvesting date response, indicates that early harvesting not only removes nitrogen but that other vital nutrients are possibly removed and will therefore need replacing.

5 CONCLUSION

Both miscanthus and switchgrass could be considered for alternative non-thermal energy conversion processes. The yield of miscanthus will remain stable and productive for several years without the need for extra nitrogen fertilizer. However after continuous early harvesting, dependent on the crop environment, some additional nitrogen will be required to maintain the crop.

Upland switchgrass can also maintain a high yield when the crop is harvested early regardless of nitrogen inputs. Although after 6 years of continuous early harvest, the yield of the upland switchgrass dramatically declined and this may suggest that other nutrients as well as nitrogen may be being depleted in an early harvested crop and that a higher application of N is required than was applied in this study. The possibility of early harvest of lowland switchgrass in Northern Europe is more problematic. Lowland switchgrass requires a killing frost before a full translocation of nutrients back to the belowground nutrient reservoir. Harvesting before this time may be possible but will require a range of plant nutrient inputs including a high application of nitrogen to maintain yields.

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