OPTIMISATION OF MISCANTHUS HARVESTING AND STORAGE STRATEGIES

B/CR/00745/00/00
URN 03/1633

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First Published 2003

SUMMARY

One of the major constraints to the utilisation of the energy crop miscanthus in the most efficient manner possible for energy production is the sub-optimal development of the harvesting and handling logistics. The report covers the first year of a three year evaluation of miscanthus harvesting and storage systems.

During the reporting period field studies at two sites were initiated, whereby different cutting/harvesting systems were compared, in factorial combinations of:

Harvesting/ baling Machinery
Timing (autumn or spring harvesting)
Post-cut biomass treatment

Experimental miscanthus plots were harvested at Boxworth (Cambridgeshire) and Woburn (Bedfordshire). All autumn harvested plots were cut with either a rape swather or mower conditioner, on 18 October 2001. Cut stems were left in the swath until baling on either 6 November or 6 December. Spring harvest took place on April 4 at 2002 Boxworth and Woburn, with straw left in the swath until 9 April (early baling) or 18 April (late baling). Leaving stems in the swath resulted in no additional drying of biomass. Harvest and baling using the mower conditioner/baler system resulted in significantly greater biomass recovery than using the rape swather/baler system. This was primarily due to the stem splitting achieved in the mower conditioner treatment allowing easier biomass pick-up. Also, the mower conditioner left less biomass in field because the cut height of the mower conditioner was lower, resulting in a much lower yield of stubble left in-field (marginal difference in autumn harvesting but a four-fold difference in the spring harvest). Both harvesting systems were modified in the spring to reduce the cut height successfully. The snapped stems produced by the mower conditioner were far easier for the baler to collect. The mower conditioner produced a swath with different dimensions to that of the rape swather, with the mower conditioner producing a smaller, lower swath. At the end of the first year’s work further refinements were considered in harvesting system, including reducing the height of the cutting blades of the mower conditioner and modifying swath structure.

Detailed monitoring of stem drying rate under controlled and ambient conditions in the swath was undertaken at Boxworth in autumn and spring and the data collected consistent with the development of crop drying model.

The impact on future productivity of harvesting at different times and systems in the year was assessed at both sites. Rhizome damage and soil compaction were monitored after both harvests. No evidence of compaction was seen but both harvesting systems damaged rhizome buds (although there were no differences between treatments). It was too early in the project to deduce significant effects of harvest timing.

In summary, significant progress was made in this initial year in improving the harvesting efficiency of miscanthus. The mower conditioner – baler harvesting system was demonstrated to be superior in terms of biomass collection and baling ease and future improvements should focus on this basic system. Swath drying remains to be demonstrated to be a suitable management tool. Within the one season of this experiment the drying rates of the miscanthus were described by the general logistic function $\log E(\mathrm{Y}) = \beta^1{}_0 + \beta_1 \log \mathrm{X}$.

More than one season’s data is required for the development of a more sophisticated model but the data generated to date will be utilised in future projects to achieve this. The experiment was in too early a stage to draw any conclusions from soil compaction measurements, from rhizome bud damage levels following harvest or from crop nutrient levels at harvest.

This grant has now terminated. Work is continuing, with Bio-Renewables Ltd as grantee, under NRE Programme grant B/CR/00797.

CONTENTS

1. Background

Miscanthus, a perennial grass that produces cane-like stems, is likely to be suitable for combustion in straw burning and mixed feedstock biomass boilers and has a wide cropping range in the UK (Price *et al.*, 2003). Studies during the last decade have indicated high crop yield potential of this species and miscanthus is now eligible for planting grants under the Energy Crop Scheme of the England Rural Development Programme (Defra, 2001).

Preliminary studies have indicated that miscanthus can be direct cut and baled, or baled following swathing, using conventional grassland and cereal straw harvesting machinery. However, there is still significant uncertainty about the most appropriate time to harvest, the extent of compaction in harvested soils, the chemical and moisture content of baled material and the optimum equipment to use. Early experience of harvesting miscanthus in the UK is that significant amounts of straw and cane remain uncollected.

Existing, unmodified machinery tends to leave a high proportion of biological yield unharvested. Convention indicates that miscanthus should be harvested in February/March on frosted ground. European studies (Jones & Walsh, 2000) have presented evidence supporting harvest windows in January – March in continental Europe However, an autumn harvest may increase the quantity of biological yield recovered, as more leaf will remain attached to stems. It will also provide more likelihood of suitable soil conditions for harvest, thus providing a greater harvest window. The warmer autumn temperatures will also provide a better crop-drying environment. In contrast, autumnal harvests may increase the nutrient off-take of the crop, increasing the risk of power station fouling (Lewandowski & Kicherer, 1997; Jorgenssen, 1997) and increasing the need for additional fertiliser applications to replace crop losses. Very early harvests in autumn may have an effect on crop vigour, if harvest is carried out before soluble carbohydrates have completely translocated to the rhizomes. This project will address all of these issues over a three year timescale.

1.1 Objectives

- To determine the most appropriate harvesting window (autumn or late winter) for efficient biomass recovery.
- To identify the impact of compaction on crop regrowth.
- To refine cutting and baling operations in order to collect the highest proportion of biomass from the field.
- To Identify the behaviour of chopped and baled miscanthus under long term storage in field conditions, and the energetic behaviour of the resultant feedstock.
- To quantify breakdown characteristics; moisture content, spore production and leachate production in bale stacks and chip piles.

This report covers work done in year 1, which concentrates on objectives 1 and 2 and starts collecting information for the other objectives.

2. Methods & Materials

2.1 Field trial establishment

The field work in this study was undertaken in year 1 at two field-scale experimental sites that had been established for previous Defra-funded studies. A subset of all original treatments was used in the current work. The establishment techniques used and experimental design of the entire fields are described below.

2.1.1 Experimental design

The experiment design was split plot, with planting system as the main plot factor and rhizome provenance as the subplot treatments. At each site, three replicate blocks of the following factorial combination of treatments were established:

<u>Planting machine type</u>
Semi-automated Potato planter
Broadcasting (using a calibrated farmyard manure spreader)
Specialist miscanthus planter

<u>Only the Semi-automatic Potato planter and Specialist miscanthus planter plots were utilised in this DTI-funded harvesting study.</u>

2.1.2 Rhizome provenance

Plots were established using miscanthus rhizomes from two sources:
a) *Miscanthus x giganteus* from UK[1] (ADAS)
b) *Miscanthus x giganteus* from Denmark (DIAS)

<u>Only plots established with UK provenance were utilised in this DTI-funded harvesting study.</u>

2.1.3 Site descriptions and site preparation.

Two experimental sites were used for this work, in Cambridgeshire (Boxworth) and Bedfordshire (Woburn). Sites were prepared by ploughing in autumn followed by secondary cultivation appropriate for the planting system employed. Full details of each site are given in Table 1.

[1] Previously identified as *M. sacchariflorus* but re-classified (Hodkinson *et al.*, 1997)

Table 1. Experimental site details.

Site Name	Grid reference	Soil type	Altitude (m)	Planting date
Boxworth	343634	Mainly Hanslope	53	11 May 2000
Woburn	496045	Stackyard Series	90	16 May 2000

The site at Boxworth was maintained by ADAS and at Woburn by IACR. All monitoring work in the DTI-funded harvesting study was undertaken by ADAS.

2.1.4 Planting detail

The target plant density was 20,000 plants ha^{-1}. Pre-planting test runs established the rhizome size range that could be used with each of the planting systems. The planters were calibrated by simulated planting on shed floors drawing the machinery across at constant speeds.

2.2 Mechanical harvest

Factorial combinations of cutting/harvesting system and harvest time were examined. The sites were cut using either a Class Rape Swather or a John Deer 1365 mower conditioner in autumn and spring.

Plots were marked out at both Boxworth and Woburn, on 17 October. All autumn harvested plots were then cut-down with either a rape swather or mower conditioner, on 18 October (DM% 29.5 & 28) . On the 6 November the first treatments were baled at both sites (DM% 58.9 & 58). On the 6 December the second treatments were baled (DM% 43 & 48.5). The spring-harvested plots were cut on the 4 April (DM% 85 &77) and all plots baled on 18 April (DM% 86 & 83.5).

The forward speed and workrate were recorded of all mechanical operation on the site. Using a stopwatch to time the progress of each machine along a plot length.

2.3 Stem moisture content

A handful of stems were collected from the swath and the bale at each harvest date, and the samples were be put into bags and then sealed and taken back to the ADAS Arthur Rickwood site shortly after cutting for fresh weight determination. The samples were dried in an oven to a constant weight at 80 ^{o}C and the dry weight recorded.

A handful of stems were cut at ground level, and the fresh weight recorded. Then the stems were then store, so that they could naturally dry and then at weekly intervals weighed.

2.4 Biomass yield

Yields were determined by harvesting to ground level all stems within two 3m x 3m areas in each of the replicates. The samples were taken back to ADAS Arthur Rickwood site as soon after cutting and the total fresh weight of the stems in each of the harvest areas was determined. Then a sub sample of 25 stems per replicate was taken and the fresh weight recorded. The stems were then stripped of leaves and the stem and leaf component were separately dried to a constant weight at 80 ^{o}C and the dry weight recorded.

All leaf litter was collected within the 3m x 3m areas in each of the replicates. The total fresh weight of the leaf litter was determined. Then a representative sub sample (c. 1 kg) was taken and the fresh weight recorded. The sub sample was then dried to a constant weight at 80 ^{o}C and the dry weight recorded.

2.5 Soil strength & soil moisture

The soil strength was measured using a penetrometer. Five readings were taken from three locations in each plot and the mean calculated

Soil gravimetric moisture content was determined by collecting a representative soil sample (c 1 kg) from the top 30 cm of each of the replicates.

2.7 Rhizome condition and weight

Three plants per sub plot were dug –up to determine the level of rhizome damage after harvest. At all stages of the sampling process the surface of the rhizome mass was protected, until the assessment had been completed. Each plant was washed to remove as much of the soil as possible, but without damaging the new shoots or buds. Once free from soil the number of new shoots per plant were counted and then the number of shoots either damaged, broken or soft to touch was recorded.

2.8 Swath dimension and characteristics

The height and diameter of every swath was measured. Placing a ruler through the centre of the swath, a record of the height from the ground to the top of the swath was taken. The diameter was measured by placing a measuring device on the outside of the swath on one side and recording the distance to the outside of the other side, at right angles to the row. These measurements were done at 5 points along every swath. The character of the swath was determined by sampling ten stems per swath. The height of each of the stems was recorded and the numbers splits/breaks or other forms of mechanical damage was recorded.

2.9 Remaining biomass

After the crop had been baled, two randomly placed quadrats per plot (2m x 2m) were used to monitor the remaining biomass on site. All leaf litter and remaining stems (down to ground level) were collected within the quadrates. The total fresh weight of the leaf litter and remaining stems were determined soon after harvest. Then a representative sub sample (c 1 kg) was taken and the fresh weight recorded. The sub samples will then be dried to a constant weight at 80 ^{o}C and the dry weight recorded for both the leaf litter and remaining stems.

3. Results

3.1 Objective 1 - To determine the most appropriate harvesting window (autumn or late winter) for efficient biomass recovery.

3.1.1 Standing Biomass yields

The autumn assessment of standing yield of crops at the two experimental sites is presented in Table 2. Woburn was harvested on 19 October 2001 and Boxworth on 20 November. The sub plot information (type of planting technique used) is included since the planting techniques affected crop yield and these data allow comparison of how the cutting/harvesting systems coped with different quantities of biomass. Yields at Boxworth were significantly lower than at Woburn ($P<0.001$) and presented different technical challenges to the cutting and harvesting machinery. At Boxworth, efficient collection of the biomass was more difficult due to the lack of crop volume. There was proportionately more leaf material than stem in the Boxworth crop than Woburn. This is a common finding with Miscanthus – as the crop matures so the proportion of ratio of stem to leaf increases. The Woburn stem:leaf ratio was considered to resemble that of a mature crop (Bullard, Nixon & Heath, 1995).

Table 2. Estimated yields of *Miscanthus x giganteus* (odt/ha/yr based on 10 plants/plot sampled) in autumn 2001 at Woburn and Boxworth.

Planter Technique	Boxworth		Woburn	
	Yield	% stem	Yield	% stem
Potato planter	1.75		6.88	-
Hvidsted	2.39		8.42	-
Mean	2.07	60	7.65	72

The spring assessment of standing yield of crops at the two experimental sites is presented in Table 3. Woburn was harvested on 3 April 2002 and Boxworth also on 3 April 2002. Yields at Boxworth were again significantly lower than at Woburn ($P<0.001$). Both Boxworth and Woburn sites indicated slight yield increases from autumn harvests. This is more likely to have been an artefact of within field variation than an actual continuation of crop growth between the two sample periods.

Table 3. Estimated yields of *Miscanthus x giganteus* (odt/ha/yr based on 10 plants/plot sampled) in spring 2002 at Woburn and Boxworth.

Planter Technique	Boxworth		Woburn	
	Yield	% stem	Yield	% stem
Potato planter	2.92		8.46	-
Hvidsted	3.70		7.67	-
Mean	3.31	65	8.07	77

3.1.2 Post-cutting swath measurements

The dimensions of the post-cutting swath were measured in order to evaluate the drying environment produced by the two cutting systems. The results are summarised in Table 4 - 6.

Table 4. Estimated swath dimensions of *Miscanthus x giganteus* (cm) in autumn 2001 at Woburn and Boxworth.

		Woburn		Boxworth	
		Average width	Average depth	Average width	Average depth
Cutting technique	Planting technique	(cm)	(cm)	(cm)	(cm)
Mower conditioner	Hvidsted machine	151.7	26.2	136.9	13.4
Mower conditioner	Potato planter	163.1	31.6	205.8	22.2
Rape swather	Hvidsted machine	195.3	36.2	191.8	31.6
Rape swather	Potato planter	192.5	39.4	185.7	23.6

Table 5. Average autumn-cut swath dimensions for each harvester, both sites.

	Average width	Average depth
	(cm)	(cm)
Mower conditioner	164.4	23.3
Rape swather	191.3	32.7

Table 6. Estimated swath dimensions of *Miscanthus x giganteus* (cm) in spring 2002 at Woburn and Boxworth.

	Woburn		Boxworth	
	Average width	Average depth	Average width	Average depth
	(cm)	(cm)	(cm)	(cm)
Mower conditioner	180.8	11.4	180.97	8.17
Rape swather	194.6	23.7	201.39	12.53

3.1.3 Stem damage during harvesting

The degree of stem 'conditioning' achieved during cutting can have important effects on the drying characteristics, biomass recovery and ease of baling and final bale density. In order to evaluate this, ten stems per sub-plot were assessed for stem length, number of leaves and number of cuts or breaks, following cutting. A data summary is presented in Table 7.

Table 7. Stem damage and leaf retention of *Miscanthus x giganteus* following cutting using different systems in autumn 2001 and spring 2002 at Woburn.

	Autumn 2001 harvest			Spring 2002 harvest		
Harvester	Average stem length (cm)	Average no. leaves	Average no. breaks/ damage	Average stem length (cm)	Average no. leaves	Average no. breaks/ damage
Mower Conditioner	152.0	2.2	1.9	136.8	0.0	1.0
Swather	174.3	4.4	0.4	150.7	0.3	0.3

3.1.4 Stubble yields

Following harvest of the miscanthus lying in swaths an assessment of stubble yield and leaf litter yield was undertaken (Table 8).

Table 8. Stubble yields (stubble + leaf litter) of *Miscanthus x giganteus* (odt/ha/yr) in a) autumn 2001 and b) spring 2002 at Woburn and Boxworth (data presented is an average of two planting techniques).

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a)	Woburn		Boxworth	
	DM yield (t/ha)	% of Total yield	DM yield (t/ha)	% of Total yield
Mower conditioner	1.5	19	0.56	27
Rape Swather	2.1	26	0.63	30

b)	Woburn		Boxworth	
	DM yield (t/ha)	% of Total yield	DM yield (t/ha)	% of Total yield
Mower conditioner	0.12	1.5	0.06	2
Rape Swather	0.62	7.7	0.23	9

2.1.5 Harvested yields

Harvested yield was calculated from the formula

$$Y_h = Y_t - Y_s$$

Where Y_t = total biomass assessed from standing crop, Y_s = Stubble biomass and Y_h = harvested biomass (Table 9).

Table 9. Harvested yields (stubble + leaf litter) of *Miscanthus x giganteus* (odt/ha/yr) in a) autumn 2001 and b) spring 2002 at Woburn and Boxworth (data presented is an average of two planting techniques).

a)	Woburn		Boxworth	
	DM yield (t/ha)	% of Total yield	DM yield (t/ha)	% of Total yield
Mower conditioner	6.15	80	1.51	73
Rape Swather	5.55	73	1.44	70

b)	Woburn		Boxworth	
	DM yield (t/ha)	% of Total yield	DM yield (t/ha)	% of Total yield
Mower conditioner	7.95	99	2.65	98
Rape Swather	7.44	92	2.48	92

2.1.6 Cutting speed

An assessment undertaken at Woburn in autumn indicated that the Mower conditioner (forward speed 1.05 m/s +/- 0.3) cut an equivalent area 28% faster than the oilseed rape swather (forward speed 0.82 m/s +/- 0.2)

2.1.7 Crop/swath moisture content

Assessments were taken of moisture content and rates of moisture loss in miscanthus stems stored either under swath conditions or removed at varying times post harvest and then stored under covered conditions.

Autumn harvested miscanthus (Figures 1 & 2) had an initial dry matter content of 30% at both sites and subsequently dried to 60%. However, rainfall events reduced moisture content back to 30% at the end of the swathing interval at Boxworth, indicating the importance of timing the removal of the miscanthus at the driest period. The re-drying profile following any rain event was determined by the amount of rain received and subsequent climatic conditions, as well as the moisture content of the soil surface.

Dry matter content of the biomass harvested in spring was much higher and more stable to climatic conditions (Figures 3 and 4). These high dry matter contents were higher than normally encountered and were an artefact of a dry early spring combined (probably) with the immaturity (and thus low stem density) of the miscanthus plants providing a more suitable drying micro-climate. Conventional practice is to bale immediately following cutting; an appropriate strategy in this instance.

Figure 1. Dry matter development of swath over time at Boxworth following autumn cutting

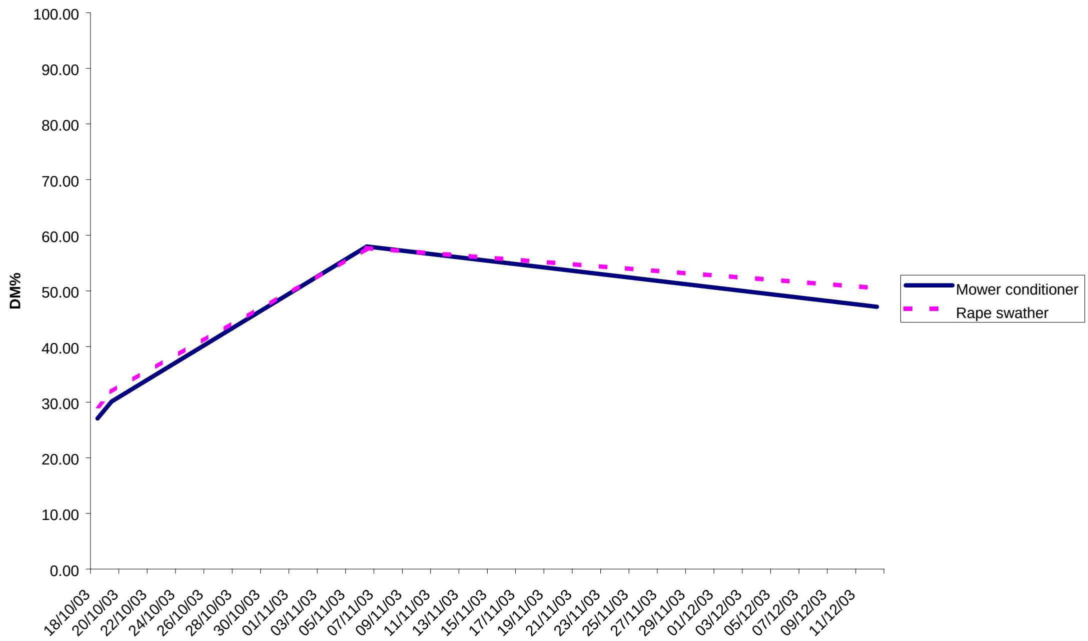

Figure 2. Dry matter development of swath over time at Woburn following autumn cutting.

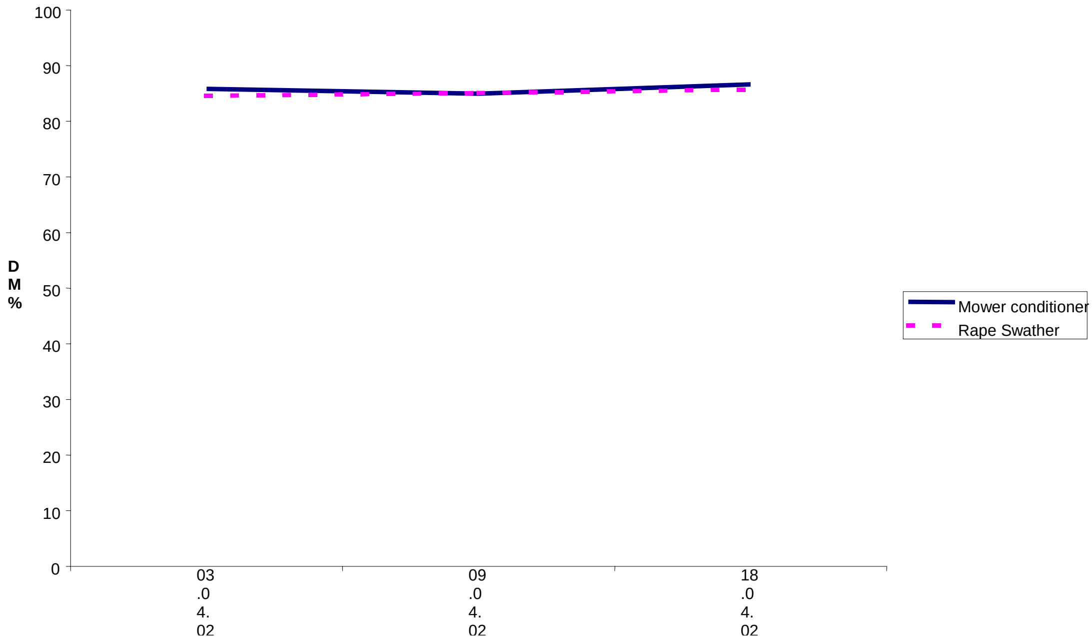

Figure 3. Dry matter development of swath over time at Boxworth following spring cutting.

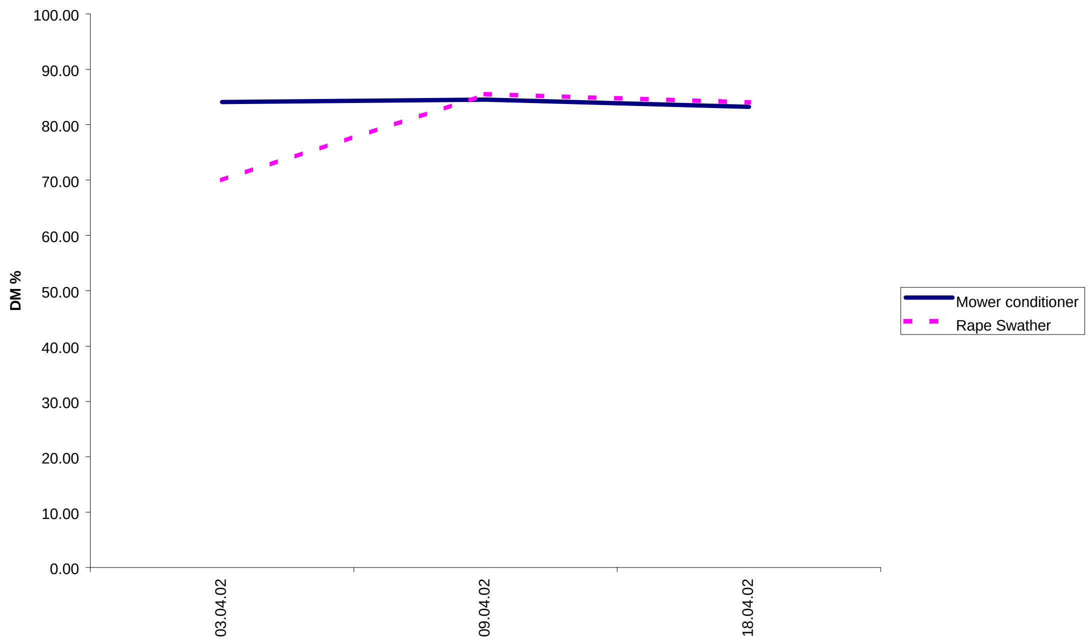

Figure 4. Dry matter development of swath over time at Woburn following spring cutting.

2.1.8 Crop drying and swath drying model development

The moisture loss studies indicated that the moisture loss curves for biomass taken at a range of initial moisture contents was the same, with the general exponential form;

$$\log E(Y) = \beta^{1}_{0} + \beta_{1} \log X.$$

The most rapid period of moisture loss was the first 2 days following removal from field. The data indicated that, irrespective of starting moisture content a similar drying curve was shown. However, generally speaking the dryer the material at the beginning of the drying process the higher the dry matter content in the equilibrium phase, and the longer the biomass took to reach equilibrium (Figure 5- 7).

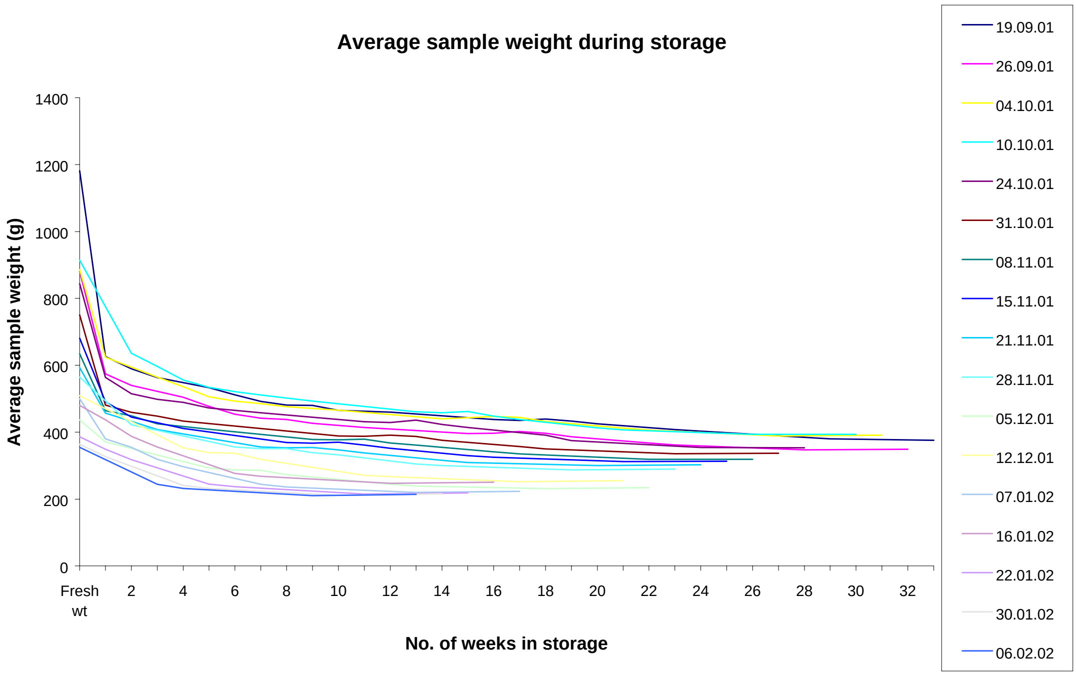

Figure 5. Covered stem crop drying progress curves

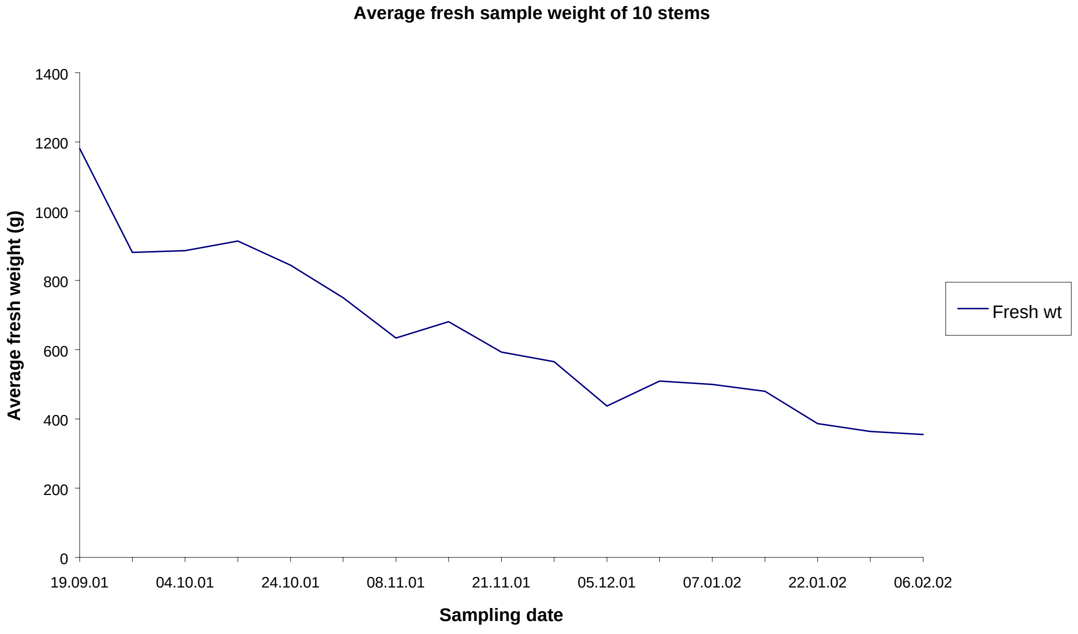

Figure 6. Rate of harvested stem drying ($Y=969.47\ e^{-0.0117}.X$)

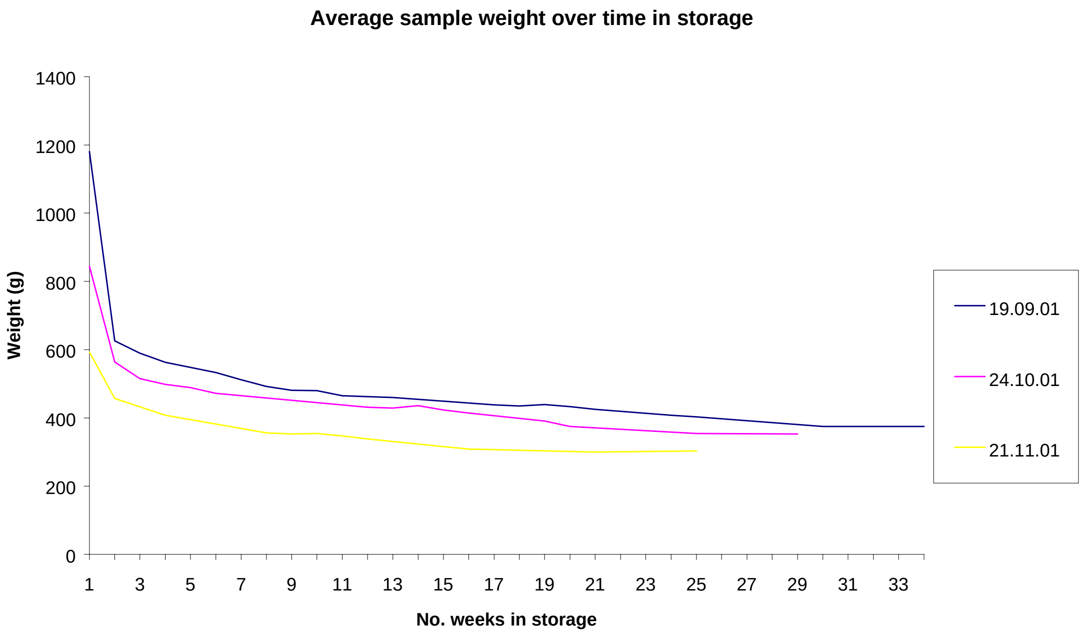

Figure 7. Drying characteristics of biomass sampled from swath at different times

3.2 Objective 2 To identify the impact of compaction on crop regrowth

Three sets of penetrometer readings were taken in each sub-plot on a tractor wheeling, and one set of readings in a control area with no wheelings. The force in kg/cm^2 needed to penetrate the ground was then calculated for each harvesting machine, at each depth (Figure 8 & 9).

Woburn - (Autumn)

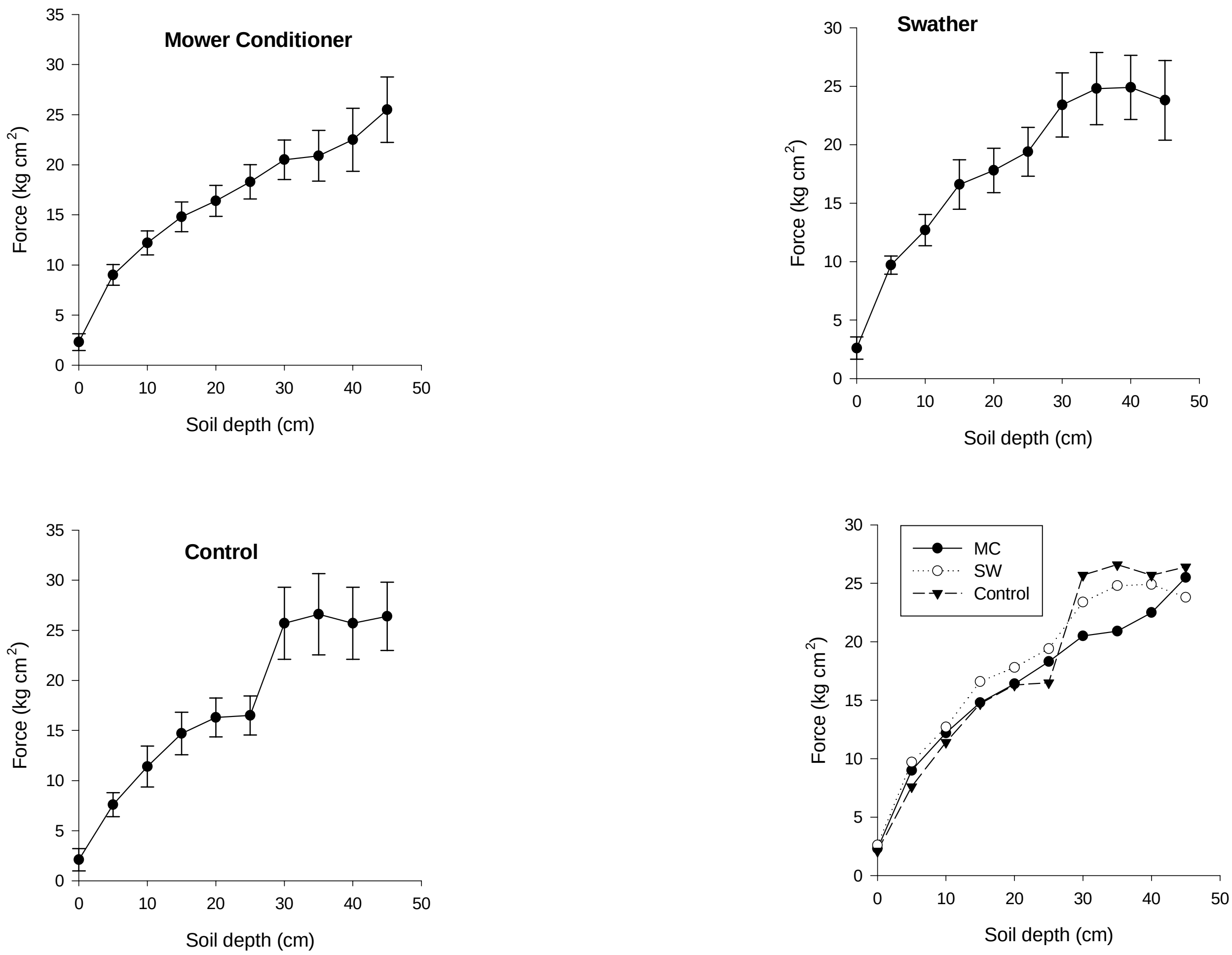

Figure 8. Soil strength following different autumn harvesting options at Woburn.

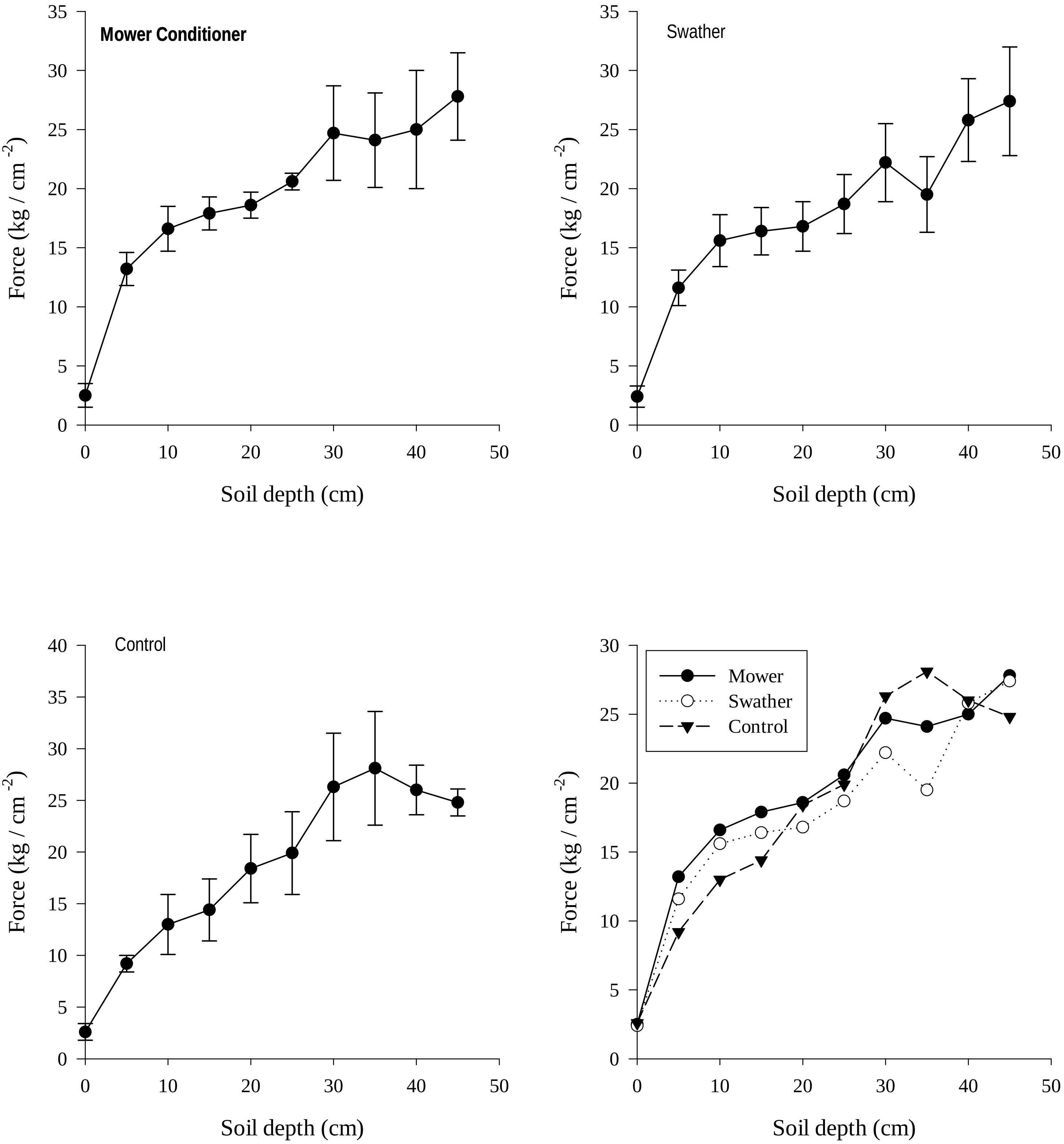

Figure 9. Soil strength following different Spring harvesting options at Woburn.

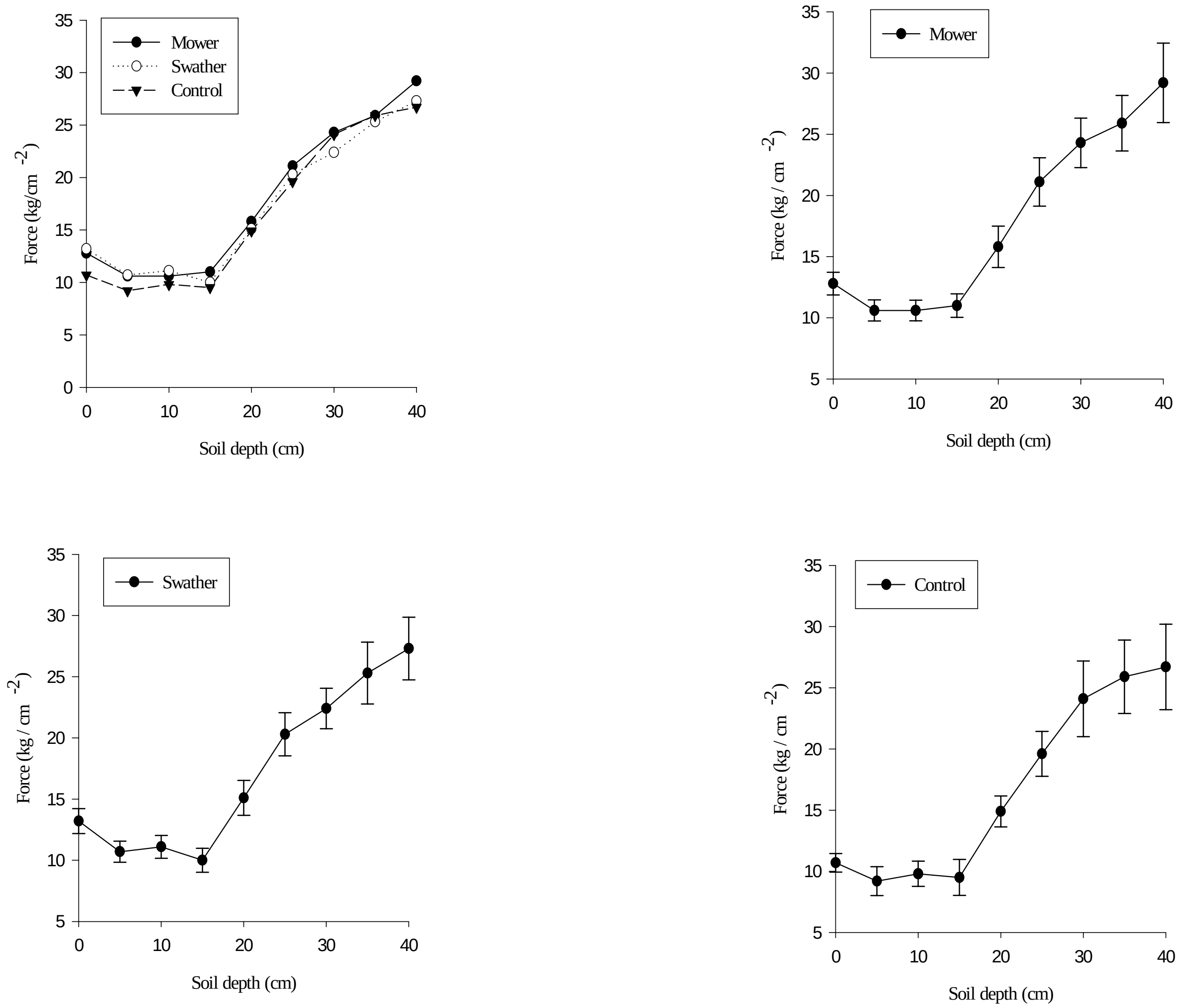

Figure 10. Soil strength following different autumn harvesting options at Boxworth.

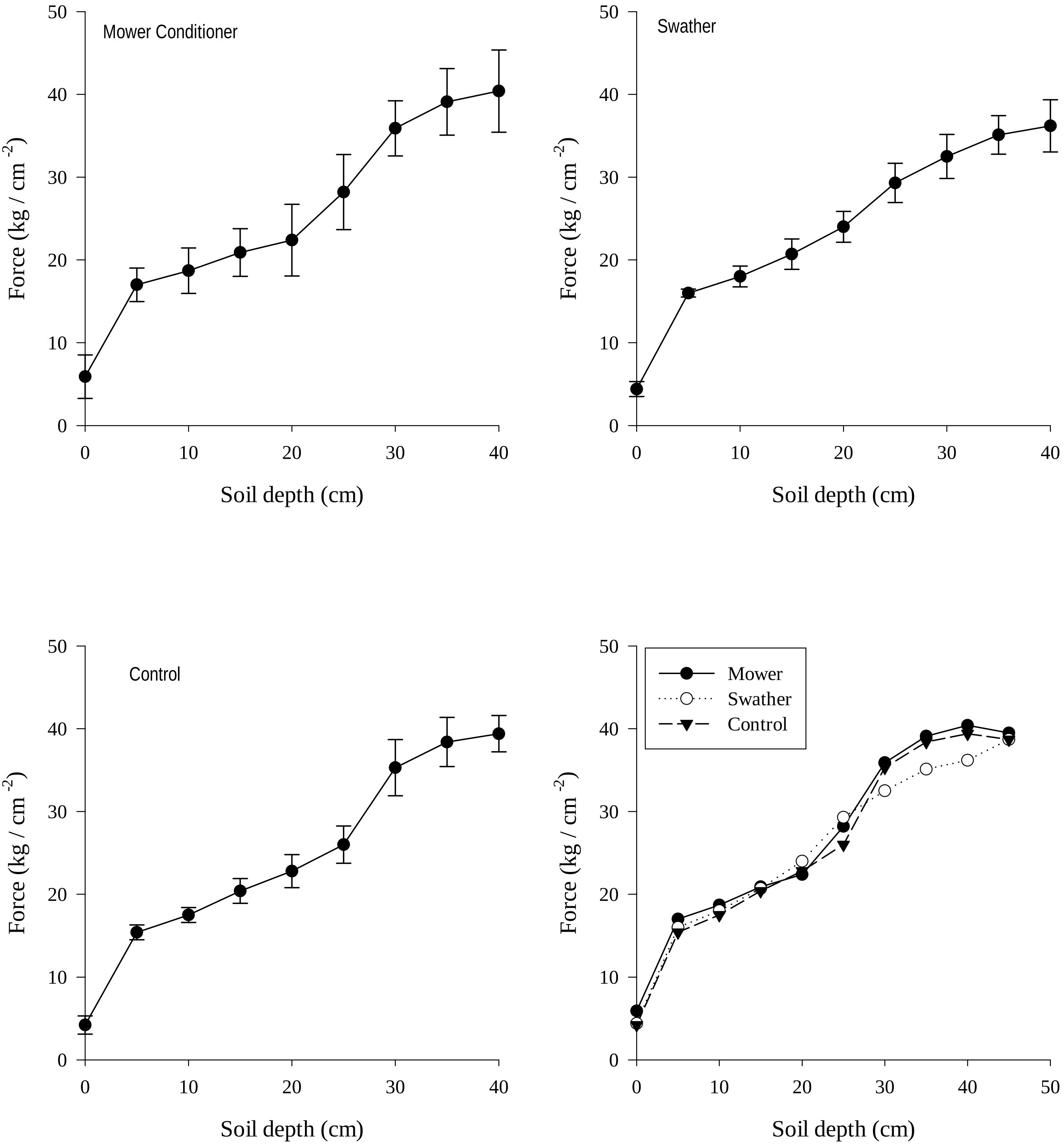

Figure 11. Soil strength following different spring harvesting options at Boxworth.

3.2.1 Rhizome damage

After harvesting and baling, six plants were dug up from each plot. Three from an area where the plants had been run over, and three from an area that had not been run over. The soil was washed off the rhizomes using a pressure washer and then the exposed new buds assessed for damage. At both sites that harvesting operation caused significant levels of bud damage, although there were no differences between the cutting systems examined.

Table 10. Percentage of damaged rhizome shoots on miscanthus before and after harvesting operations.

	% damaged shoots	
Site	Pre-harvest	Run over
Boxworth	9.0	19.6
Woburn	16.1	27.9
Average	12.5	23.7

3.3 Objective 3 - To refine cutting and baling operations in order to collect the highest proportion of biomass from the field.

Video recording were taken of the cutting and baling actions for all systems assessed in the first year.

During the first harvest using the rape swather a number of problems were encounter: -
1) the knives stalled
2) reel block with material (this problem was solved by moving the reel forward)

Problems with the mower conditioner were also encountered, namely stones being picked-up and thrown through the rear window of the Tractors. Subsequent modifications will minimise this risk.

The use of a tedder was suggested to increase total harvestable yield and to produce a more even swath to enable more efficient baling. This will be investigated in future work.

The average weight of the bales was 520 kg. These bales were slightly shorter than the standard Hesston Bale dimension. Bales being produced from material cut by the rape swather were tended to be rough, in that stems protruded from the side of the bale and then they were handle by the bale handling equipment at the Elean power station - this caused some problems in the power station’s bale handling system. No such problems were encountered from bales that had been conditioned.

Given that the fundamentals of the oilseed rape swather cutting systems was found to be fundamentally deficient the technique was discounted for subsequent usage. Consequently machinery modifications focused on the mower-conditioner and Square baling system. Between autumn and spring harvests a number of modifications were made to the cutting height of both the conditioner and the rape swather. In autumn, where a good drying environment was needed for the cut stems the cutters were kept high in order to keep the swath from ground contact. As a consequence stubble heights, and yield, were high. In spring, where direct harvesting was more likely since the standing biomass dry matter content was much higher a low stubble was cut. This consequently boosted recovered yield considerably.

3.4 Objective 4 - To identify the behaviour of chopped and baled miscanthus under long term storage in field conditions, and the energetic behaviour of the resultant feedstock.

Baled miscanthus was accumulated for this component of the work but no experimentation was undertaken (or anticipated in the work plan) in the first year.

No work on chipped miscanthus for objectives 4 and 5 was initiated in this first year.

3.5 Objective 5 - To quantify breakdown characteristics; moisture content, spore production and leachate production in bale stacks and chip piles.

Baled miscanthus was accumulated for this component of the work but no experimentation was undertaken (or anticipated in the work plan) in the first year

4. Discussion

From the interim report presented and the data gathered it was clear that the mower conditioner/baler combination was the preferred harvesting system because it provided;

- More efficient biomass recovery
- Better swath dimensions
- More rapid activity
- Greater stem conditioning, enabling,
- Better bale formation

Within year, we were able to implement some changes to the harvesting mechanisms which significantly increased the quantity of biomass recovered. The balance between leaving a high stubble, on which an aerated and rapidly drying swath is held, and choosing to cut as close to the ground to maximise biomass recovery (i.e. the compromise between quality and quantity) has not within the first year of the work, been resolved.

The data collected indicate that a swath drying model will be easily achieved. However, more than one season’s data are needed before a robust model can be delivered.

4.1 Amendments to future workprogramme

During the course of the first year of this project the industrial sponsor made clear their intentions to discontinue the project at the end of the first twelve month period The work is now being continued as NRE project B/CR/00797.

5. References

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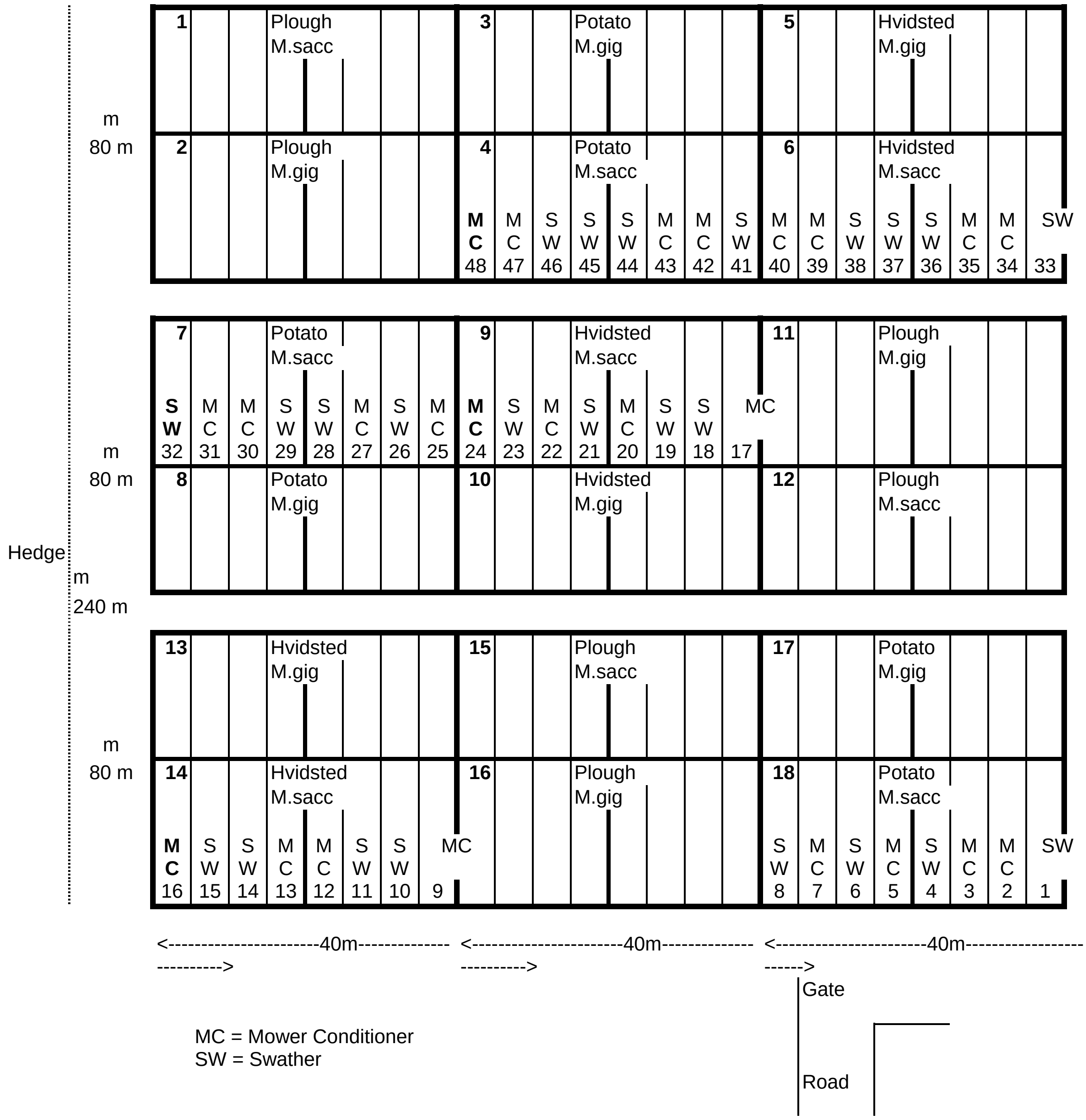
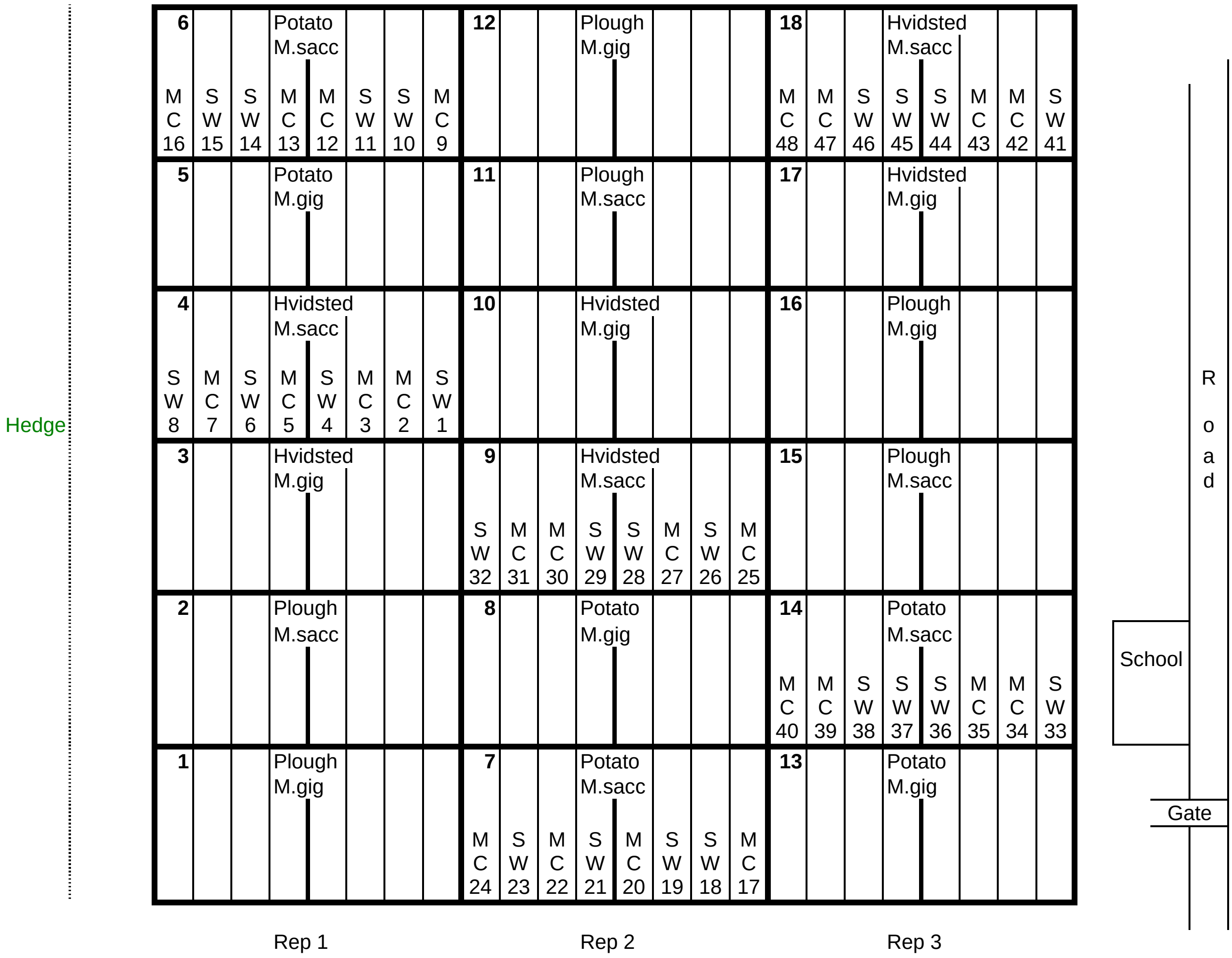
6. Annex- Trial designs

Trial plan - Boxworth



Trial plan - Woburn



MC = Mower Conditioner
SW = Swather