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Effect of Harvest Timing and Soil Moisture Content on Compaction, Growth and Harvest Yield in a Miscanthus Cropping System

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Abstract: Harvesting *Miscanthus* × *giganteus* (J.M. Greef & Deuter ex Hodkinson & Renvoize) after shoot emergence is known to reduce yields in subsequent seasons. This research was conducted in *Miscanthus* to assess the effects on crop response and soil compaction of annually repeated traffic, applied both before new growth in the rhizomes (early harvest) and after shoot emergence (late harvest), at two different soil moisture contents. While an annual early harvest, yields more than a late harvest, because damage to new shoots is avoided, soil compaction may be increased following repeated harvests. Five treatments were tested: (a) An untrafficked control, (b) early-traffic on soil with typical soil moisture content (SMC) (early-normal), (c) early-traffic on soil with elevated SMC (early-elevated), (d) late-traffic on soil with typical SMC (late-normal) and (e) late-traffic on soil with elevated SMC (late-wet). The experiment was conducted on a Gleysol in Co. Dublin, Ireland during 2010 and 2011. Crop response effects were assessed by measuring stem numbers, stem height, trafficked zone biomass yield (November) and overall stem yield (January). Compaction effects were assessed by measuring penetration resistance, bulk density and water infiltration rate. Trafficked zone biomass yield in the early-dry and early-wet treatments was, respectively, 18% and 23% lower than in the control, but was, respectively, 39% and 31% higher than in the late-dry treatment. Overall, stem yield was significantly lower in the late-normal and late-wet treatments (10.4 and 10.1 tdm ha^{-1} respectively) when compared with the control (12.4 tdm ha^{-1}), but no significant difference was recorded in overall stem yield between both early-traffic treatments and the control. Penetration resistance values were significantly higher in all trafficked treatments when compared with the control at depths of 0.15 m (≥54–61%) and 0.30 m (≥27–57%) and were significantly higher in 2011 when compared with 2010 at depths of 0.15 and 0.30 m. Baler system traffic in *Miscanthus* significantly reduced yields and significantly increased compaction annually. *Miscanthus* harvested early, on a dry soil, yielded 1.1 tdm ha^{-1} more than when harvested late on a dry soil. The yield advantage increased to 1.3 tdm ha^{-1} when early harvesting on a soil with 40–43% moisture content was compared with late harvesting on a wetter soil (51–52% moisture content). In this study, the magnitude of yield losses from compaction or other causes in early harvests was substantially lower than the yield losses, which resulted from shoot damage in late harvests. It is likely in similar climates that the results of this study would also apply to other perennial crops growing in similar soil types.

Keywords: *Miscanthus*; repeated trafficking; compaction

1. Introduction

Ireland faces similar energy challenges to those being confronted worldwide. This situation is made more acute by limited indigenous fuel resources, peripherality and a small energy market. There are major opportunities to be realised in harnessing the full potential of renewable energy sources [1] as they produce significantly lower concentrations of environmental pollutants when compared with conventional energy sources and can be and sustainably produced. The most common form of renewable energy is biomass, which includes all plant based organic material [2].

Miscanthus × *giganteus* (subsequently referred to as *Miscanthus*) possesses the efficient C_4 photosynthetic pathway (with relatively low nutrient and water requirements) and is tolerant of cool temperate climates, which makes it an "ideal" energy crop [3]. *Miscanthus* also has the advantage of an annual cropping cycle that provides a regular income for the grower [4]. Field experiments have shown that *Miscanthus* is capable of producing annual dry matter yields of biomass in excess of 20 t ha^{-1} in suitable sites [5] and rotations are estimated to be from 15 to 25 years [3].

More than 2700 ha of *Miscanthus* for biomass production have been planted in Ireland and at harvest in spring (March or early April), the crop is mown and baled. Alternatively, it can be cut and chipped using a forager equipped with a row independent maize header [6]. *Miscanthus* should be harvested annually before new shoots emerge to avoid damage by harvest equipment to the new shoots [7–9].

Lack of understanding of the impact of traffic on subsequent miscanthus shoot emergence has caused a negative response in growers to the crop. Soil conditions at harvest time must be assessed to minimise the damage caused by the weight of the harvesting equipment on the soil structure [7]. Dry soil resists compaction [10], but as water content increases, soil becomes more easily compactable. [11] reported that water content is the most important factor influencing soil compaction processes.

Soil compaction is a stress factor that negatively affects plant growth [12,13] observed that the productivity of perennial crops may be seriously reduced as a result of adverse effects attributable to direct crop damage from the passage of wheels. More recently [14] reported that decreased yields in meadow fescue (*Festuca Pratensis*) following tractor traffic were likely as a result of damage caused to above-ground parts of plants. In *Miscanthus*, O'Flynn et al. [15] found that stem yield losses of 1.8 tdm ha^{-1} were caused by the adverse effects of high inflation tyre pressure of harvest machinery on newly emerged shoots.

Tolon-Becerra et al. [16] working with wheat (*Triticum* spp.) recorded trafficked yield decreases of 18%, 22%, 30% and 38% following 1, 3, 5 and 7 passes respectively of a heavy tractor (8160 kg) when compared with the untrafficked control. Four passes on the same location compacted a clay soil to 0.50 m depth [17] with penetrometer resistance readings being 22% to 25% greater in the compacted treatments when compared with the control (untrafficked treatments). In energy crops (short rotation coppice, willow—*Salix viminalis* L.), heavy compaction reduced stem biomass production by approximately 12% overall and increased soil strength and bulk density down to a depth of 0.40 m [18].

With the recent increased interest in *Miscanthus* and the reported negative effects of harvest traffic on compaction and yields in energy crops [7,8,15,18], it has been recognised that further studies should be carried out into the impacts of harvest traffic operating in commercial *Miscanthus* crops as recommended by [19].

Previous work had shown that harvesting after shoot emergence can result in substantial reductions in yield and suggested that all field operations should be completed before the initiation of new growth [15]. Subsequent work had investigated the effect of annually repeated traffic from different harvesting systems on subsequent growth and productivity [9]. Both of these studies concentrated on the effect of harvest traffic after the initiation of new growth. However, the consequences of early harvests on subsequent growth and development had not been studied previously and it is possible that compaction or other effects during early harvests could also reduce yield. Thus, the specific objectives of this work were to: (a) Determine if *Miscanthus* harvested early (February, before all new growth), using the baler harvest system, yields more than when harvested late (April, after shoot emergence), (b) assess the effect of baler system traffic on soil compaction in *Miscanthus*, when operated early (February) in wet and dry soil conditions and late (April) in wet and dry soil conditions. This study was conducted on a heavier soil type, which is sensitive to trafficability with higher rainfall compared to the previous studies.

2. Materials and Methods

2.1. Site, Treatments, Equipment and Experimental Plots

Experiments were conducted in 2010 and 2011 at University College Dublin Lyons Research Farm, Newcastle, Co. Dublin, Ireland (53°18′27.58″ N, 6°31′57.95″ W) in a *Miscanthus* crop established in 2007, growing at an elevation of approximately 70 m above sea level. The soil is described as a silty loam to silty clay loam [20] and is classified as a Gleysol [21]. A soil pit was excavated manually to a depth of 1 m in 2007, adjacent to the experiment area to visually examine the soil profile, soil structure and root growth. Particle size distribution of the soil profile is shown in Table 1. Volumetric soil water content to a depth of 12 cm was measured.

Table 1. Soil particle distribution (g kg^{-1}) of the profile pit at the experimental site.

Depth (m)	Coarse Sand (2.0–0.5 mm)	Medium Sand (0.5–0.25 mm)	Fine Sand (0.25–0.05 mm)	Silt (0.05–0.002 mm)	Clay (<0.002 mm)
0.00–0.15	71	46	200	360	323
0.15–0.28	78	45	201	364	312
0.28–0.40/0.48	91	72	289	315	233
0.40/0.48 +	107	67	234	357	235

The experiment consisted of five treatments:

1. Control—no experimental traffic.
2. Early-traffic on soil immediately below field capacity—(early-SMC as found).
3. Early-traffic on soil at field capacity—(early-elevated SMC).
4. Late-traffic on soil immediately below field capacity—(late-SMC as found).
5. Late-traffic on soil at field capacity—(late-elevated SMC).

In 2009 the crop was examined daily from mid-March to establish the date that the first new shoots emerged overground; this occurred on April 14th that year. Consequently, it was decided in 2010 and 2011 that the early-traffic treatments would be applied in late February—well in advance of new growth in the rhizomes. The late-traffic treatments would be applied in late April, approximately two weeks after new shoot emergence.

The equipment used in this experiment simulated the baler harvest system and each machine matched the ground pressures exerted by components of the baler system namely: (1) Tractor and mower/conditioner, (2) tractor and large-square baler, (3) tractor and front-end-loader with bale, (4) tractor and loaded bale trailer (Table 2). Each component of the baler system was trafficked through the appropriate treatments on one occasion annually at a speed of 5.0 kph. The baler system was chosen because the equipment involved is usually available in most localities and the end user often requires product as a bale.

In January 2010, experimental plots were arranged along individual rows of *Miscanthus*. Each plot measured 35 m long and 1 m wide. There were buffer zones 9 m long between treatments along each row and trafficked rows were 10 m apart in the field. Treatments were arranged in a randomised complete block design with four replications.

Table 2. Axle loads (kg), tyre sizes and tyre inflation pressures (kPa) of the components used to simulate baler system traffic in *Miscanthus* harvesting.

Specifications of Equipment Used in the Trafficking Trials			
(1) Tractor (4 wheel drive 4WD) and Mower	Front Axle	Rear Axle	Trailed Axle
Axle load (kg)	2810	3230	1850
Tyre size	480/65 R 24	540/65 R 38	385/65/22.5
Inflation pressure (kPa)	160	160	160
(2) Tractor (4WD) and baler	Front axle	Rear axle	Trailed axle
Axle load	4040	4120	2700
Tyre size	540/65 R 28	650/65 R 38	23.1–26
Inflation pressure	160	160	160
(3) Tractor (4WD) /front loader/bale	Front axle	Rear axle	
Axle load	3360	2650	
Tyre size	480/65 R 24	540/65 R 38	
Inflation pressure	160	160	
(4) Tractor (4WD) and bale trailer	Front axle	Rear axle	Trailed axle
Axle load	3640	6560	9370
Tyre size	540/65 R 28	650/65 R 38	23.1–26
Inflation pressure	160	160	160

Forty individual plants (sample plants) of consistent size (0.50 m diameter, 2.25 m high and approximately 50 stems per plant) were selected in each treatment and marked at the start of the experiment; these plants were subsequently used to assess crop response (Figure 1). This was necessary to ensure that a consistent number and size of plants were sampled per treatment as the variable establishment rate in this *Miscanthus* crop resulted in irregular sized and/or missing plants in all experimental plot areas.

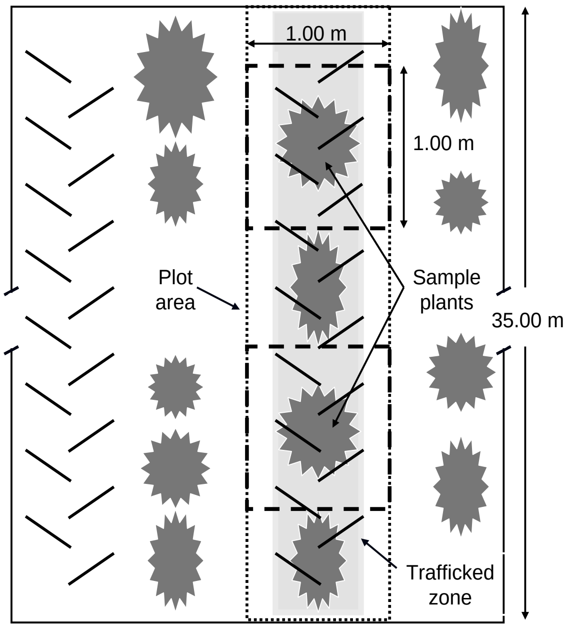

Figure 1. Experiment plot layout (not to scale) with plot area (dotted), sample plants (dashed) and trafficked zone (shaded).

The crop in the experimental areas was harvested in January 2010, in a manner that prevented wheel traffic on the experimental rows, in advance of applying the initial treatments. In January 2011 and 2012 the crop in each treatment was harvested by hand to assess overall stem yield and clear the experimental area for the next application of treatments. The crop received no inputs with regard to nutrients or plant protection products throughout the duration of the study.

Electronic weighpads (Cheklode Freeweigh Model FW-LCF 10, Kidderminister, UK) measured the static axle loads of all equipment. Tyre inflation pressures were adjusted to 160 kPa on all wheels. This inflation pressure represented what was required for high-speed road-transport purposes (40 kph) rather than for soil sensitive values [15].

The wheels on one side of a traffic component (example right-hand-side wheels of the tractor and baler combination) were driven along the selected row of *Miscanthus*. It is accepted that in the baler system the tractor/loader/bale and tractor/bale trailer components move in a somewhat random manner across the field and do not travel directly on the wheel tracks of the tractor/mower and tractor/baler components; this implies that a worst-case scenario was tested in this experiment regarding intensity of trafficking.

Treatments were applied on February 20th and April 24th in 2010 and on February 26th and April 22nd in 2011 when the soil water content was lower than field capacity following dry weather. Wet soil conditions were achieved by irrigating the appropriate treatments until they were saturated and allowing the soil to drain naturally until it was at field capacity.

The two soil water conditions tested in this experiment represent, during a *Miscanthus* harvest, both a worst-case scenario (field capacity) and an optimal scenario for late February in Ireland (immediately below field capacity) with regard to the vulnerability of soil to compaction during trafficking operations.

2.2. Measuring Soil Water Content

Soil water content (volumetric) was measured to a depth of 0.12 m with a HydroSense Soil Water Tester (Campbell Scientific, Logan UT, USA). This device uses 'time domain reflectometry' and consists of a sensor with two 0.12 m probe rods connected to a display/control unit. Forty measurements were conducted in each treatment prior to applying harvest traffic annually, by fully inserting the probe rods into the soil and taking a reading from the display.

2.3. Assessing Crop Response

Crop response was assessed in 2010 and 2011 by measuring crop regrowth (stem numbers and stem height) and crop yield (trafficked zone biomass yield in November and overall stem yield in January).

Crop regrowth was assessed on a weekly basis between May 1st and October 31st annually. Stems were counted (stems m^{-2}) and height was measured (average distance from ground level to the top-most leaf ligule) in the sample plants of all treatments.

Biomass yield was assessed in November by harvesting 16 sample plants by hand in each treatment when senescence was well advanced, but before significant leaf loss from the plants. Overall stem yield was assessed in January by harvesting 16 sample plants by hand in each treatment when leaves had dropped from the stems. The procedures for assessing trafficked biomass yield and overall stem yield are similar to those outlined in Reference [15], except that in this experiment, adjustments were made to take account of the establishment rate and the proportion of field area trafficked in the baler system. Crop yields were calculated in tonnes of dry matter per hectare (tdm ha^{-1}).

2.4. Assessing Soil Compaction

Soil penetration resistance (SPR) was determined using an Eijkelkamp penetrologger Model no. 06.15 (Eijkelkamp, Giesbeek, The Netherlands). The technique employed when using the Eijkelkamp Penetrologger in the field was as recommended by the manufacturers and as set out in ASAE Standard EP542 [22] and ASAE Standard S313.2 [23] Penetration resistance was assessed by performing forty penetrations per treatment and values were recorded at 0.01 m increments from the soil surface to a depth of 0.45 m and the average reading of resistance at each increment from the 40 penetrations was used. Measurements were conducted on 9 June 2010 and on 29 October 2011.

Bulk density was assessed by removing undisturbed soil cores (0.1 m), of 100 cm^3 volume, from all treatments. Four soil cores were taken at the soil surface in each treatment. Pits were then dug to a depth of 0.6 m and four soil cores were extracted at depths centred at 0.15, 0.30 and 0.45 m in each treatment. These cores were placed in plastic bags and sealed. They were weighed later (fresh soil weight) and then oven-dried at 105 °C for 72 h to get a dry weight. Dry bulk density, in grams per cubic centimetre (g cm^{-3}), was then calculated. Measurements were conducted on October 1st and 2nd in 2010, and on November 1st and 2nd in 2011.

Water infiltration rate was assessed using a double ring infiltrometer. The infiltrometer rings had diameters of 0.3 and 0.6 m and were operated in accordance with ASTM Standard D3385-09 [24]. Infiltration rates were recorded in units of centimetres per hour (cm h^{-1}). Four measurements were conducted per treatment. Water infiltration rate was measured in 2010 during the week August 3rd to 6th. Assessment was conducted in 2010 only due to the destructive nature of the process on the crop.

Detailed descriptions of the procedures involved in assessing soil compaction are included in O'Flynn et al. [15].

2.5. Meteorological Data

Meteorological data were recorded at the Casement Synoptic Weather Station, Baldonnell, Co. Dublin, Ireland. This weather station is representative of the local climate [25] and is located 6.0 km from the experiment site. During the growing seasons (April 1st to October 31st) of 2010 and 2011, average air temperature of 12.5 °C was recorded along with total rainfall of 441 mm. Average soil temperature of 13.8 °C was recorded at a depth of 0.1 m during the growing seasons (Table 3). In 2010 a soil temperature of 10 °C, the minimum soil temperature required for new growth to begin [7,8,26], was first recorded on April 11th while in 2011, this soil temperature was first recorded on March 31st [15]. Volumetric soil moisture content, on the days that treatments were applied, is shown in Table 4, along with rainfall amounts for each preceding week.

Table 3. Meteorological data in the growing seasons between April 1st and October 31st in 2010 & 2011.

April 1st to October 31st	Max. Air Temp. (°C)	Min. Air Temp. (°C)	Average Air Temp. (°C)	Total Rainfall (mm)	Average Soil Temp. at 0.10 m. (°C)
2010					
April	18.1	−3.4	8.3	32.7	9.6
May	24.9	−2.0	10.2	44.9	13.3
June	23.8	4.5	14.8	45.2	17.5
July	23.6	9.4	15.9	81.7	17.3
August	21.4	2.2	13.9	43.5	16.1
September	22.3	1.4	13.4	102.7	14.1
October	18.6	−2.5	10.1	37.7	10.3
2011					
April	21.8	0.0	10.9	30.0	11.9
May	18.1	4.1	11.4	51.5	12.6
June	22.5	2.3	12.4	65.1	14.9
July	22.9	4.7	14.1	53.1	16.6
August	22.1	4.8	13.6	51.6	15.3

Table 4. Volumetric soil moisture content (%) to 0.12 m depth, on the days that treatments were applied in 2010 and 2011. Rainfall (mm) in the week preceding each treatment date is also shown.

	Date of Soil Moisture Measurement			
Treatment	**20 February 2010**	**24 April 2010**	**26 February 2011**	**22 April 2011**
Control—no experimental traffic		0.44		0.34
Early traffic on dry soil	0.46		0.40	
Early traffic on wet soil	0.46		0.44	
Late traffic on dry soil	0.51	0.43	0.51	0.40
Late traffic on wet soil		0.52		0.51
Rainfall (mm)	2.9	0.0	15.0	6.3

2.6. Statistical Analysis

A Repeated Measures ANOVA was used to analyse data for crop response, penetration resistance and bulk density for the years 2010 and 2011. Regarding water infiltration rate, a Two-way ANOVA was used for analysis as data were collected in 2010 only. Statistical analysis was carried out using MINITAB version 15 (Minitab Inc, PA, USA). Significance was set at 5% and Tukey's honest significant difference test was used for mean separation.

3. Results

3.1. Crop Response

The Repeated Measures ANOVA analysis of stem numbers and stem height was carried out on values measured on the final monitoring date each year in October (stable final values). All weekly stem number and stem height values, over the two years of the study, are presented in Figure 2.

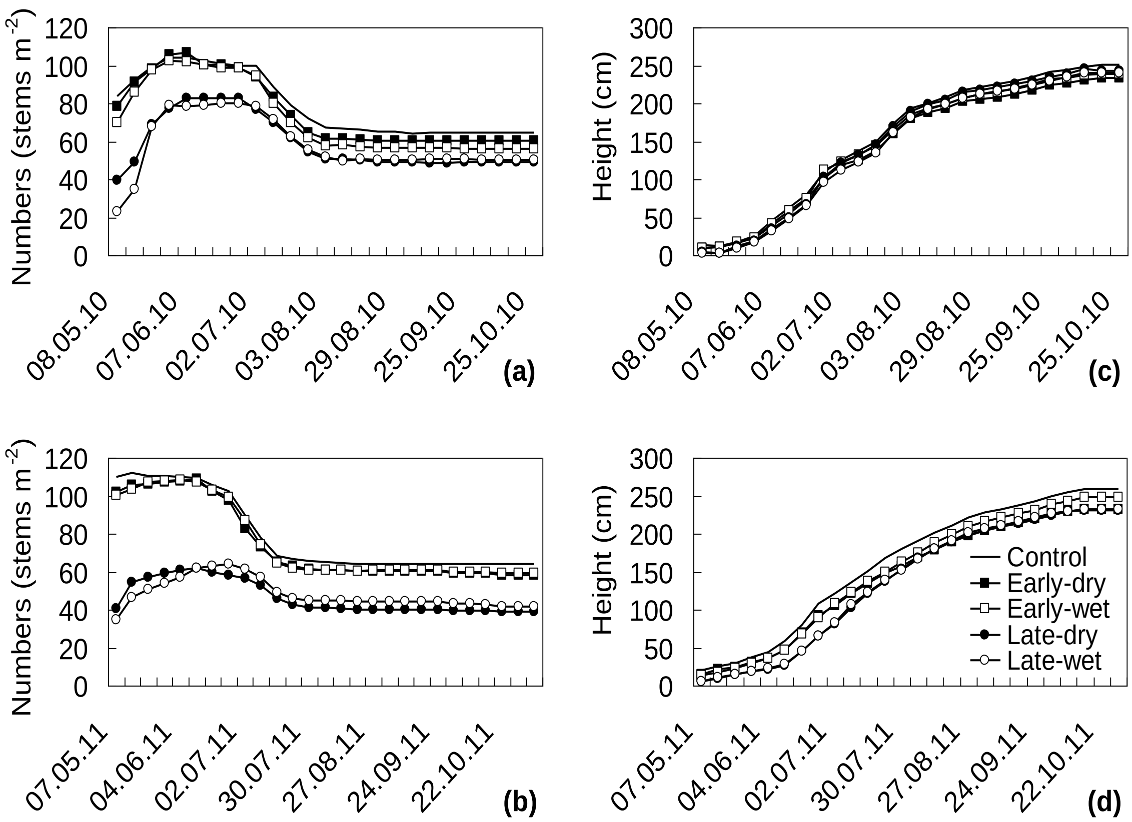

Figure 2. Weekly stem numbers (stems m^{-2}) and stem height (cm) in the growing seasons (April 1st to October 31st) 2010 (**a**,**c**) and 2011 (**b**,**d**).

3.2. Stem Numbers in Trafficked Zone

Stem numbers in trafficked zones were significantly higher in the early-dry treatment and in the control when compared with the late-dry and late-wet treatments (Table 5). Across the two years of the experiment, stem numbers in the early-dry and early-wet treatments were, respectively, 8% and 11% lower than values in the control, but were, respectively, 34% and 30% higher than values in the late-dry treatment.

Table 5. Effect of treatment and year on growth and yield parameters measured in November (Trafficked Zone) and January (Overall).

	Stem Parameters in the Trafficked Zone						
Treatment	**Stem Number (m^{-2})**	**Stem Height (m)**	**Biomass Yield (tdm ha^{-1})**	**Stem Yield**	**Green Leaf Yield**	**Senesced Leaf Yield**	**Stem Yield**
Control	64.4 a	2.55 a	24.83 a	17.77 a	4.36 a	2.69 a	12.37 a
Early-dry	59.3 a	2.33 b	20.31 ab	14.20 ab	3.47 ab	2.63 a	11.43 ab
Early-wet	57.5 ab	2.43 ab	19.04 ab	13.19 b	3.45 ab	2.38 a	11.47 ab
Late-dry	44.1 c	2.37 ab	14.57 b	10.22 b	2.70 b	1.63 b	10.42 b
Late-wet	46.0 bc	2.36 b	15.50 b	10.79 b	3.02 b	1.68 b	10.12 b
2010	56.1	2.41	21.42 a	15.34 a	3.69 a	2.38 a	11.07
2011	52.5	2.41	16.28 b	11.12 b	3.12 b	2.03 b	11.25
Interaction	ns	ns	ns	ns	ns	ns	ns

Note: Means within each column followed by the same letter are not significantly different. (ns = non-significant).

Stem numbers in the early-dry and early-wet treatments and in the control increased from mid-April (stem emergence) until mid-June each year (Figure 2a,b). Values in the late-dry and late-wet treatments at that time were lower by comparison as a result of damage to newly emerged shoots by the traffic treatments. Values from early July reduced in all treatments as die-back/self-thinning occurred. Stem numbers stabilised in all treatments in August each year and these values were maintained until growth ceased in October. In 2010, by the end of the growing season, stem numbers in the late-dry and late-wet treatments reached similar values to those in the other treatments, but in 2011 values in both late-traffic treatments were considerably lower than in the other treatments.

3.3. Stem Height in Trafficked Zone

Stem height in trafficked zones was significantly lower in the early-dry and late-wet treatments when compared with the control, but there was no significant difference in stem height between any of the trafficked treatments (Table 5). Across the two years of the experiment, stem height varied very little across all trafficked treatments (range 2.33 to 2.43 m).

Stem height in the early-dry and early-wet treatments and in the control increased each year at rates ranging from 0.01–0.06 m $week^{-1}$ from mid-April to early June. Values in the late-dry and late-wet treatments at that time were lower than all other treatments, as a result of damage to newly emerged shoots by the late-traffic treatments. Growth rates ranging from 0.07–0.25 m $week^{-1}$ were recorded from early June to mid-August in all treatments (Figure 2c,d). From mid-August to late September growth rates ranging from 0.02–0.10 m $week^{-1}$ were recorded while from late September to mid-October the rate of growth in stem height was approximately 0.01–0.02 m $week^{-1}$. It was notable by the end of the growing season each year that stem height values in both late-traffic treatments had recovered to almost match those in the early-traffic treatments.

3.4. Biomass Yield in Trafficked Zone

Biomass yield in trafficked zones was significantly lower in the late-dry and late-wet treatments when compared with biomass yield in the control (Table 5). Across the two years of the experiment, biomass yield in the early-dry and early-wet treatments was, respectively, 18% and 23% lower than in the control, but was, respectively, 39% and 31% higher than in the late-dry treatment. Stem yield was significantly reduced by early traffic under wet conditions and by both late traffic treatments, but there was no significant difference in stem yield and green leaf yield between any of the trafficked treatments although senesced leaf yield in the late-wet and late-dry treatments was significantly lower than in all other treatments. Biomass yield was lower in 2011 by 5.14 tdm ha^{-1} when compared with 2010 with all components of biomass (stem, green leaf and senesced leaf) being significantly lower in yield in 2011 (Figure 3).

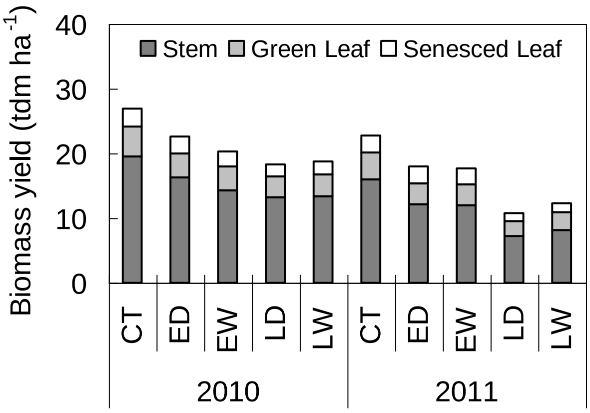

Figure 3. Stem, green leaf and senesced leaf trafficked zone biomass dry matter yield (tdm ha^{-1}) in November 2010 and 2011. CT = control, ED = early-dry, EW = early-wet, LD = late-dry and LW = late-wet.

3.5. Overall Stem Yield

Overall stem yield was significantly lower in the late-dry and late-wet treatments when compared with the control (Table 5). Across the two years of the experiment, overall stem yield in both the early-dry and early-wet treatments was 8% lower than in the control, but was 10% higher than in the late-dry treatment.

3.6. Soil Compaction

The volumetric water content, when trafficked treatments were applied (Table 4), ranged from 0.40 to 0.46 mm in the dry-soil treatments while the wet-soil treatments ranged from 0.51 to 0.52 mm. Penetration resistance was significantly higher in all trafficked treatments when compared with the control at depths of 0.15 and 0.30 m (Table 6). Penetration resistance values in both late-traffic treatments were significantly lower than those of the early-dry treatment at a depth of 0.30 m. Penetration resistance was significantly higher in 2011 when compared with 2010 at depths of 0.15 and 0.30 m. There was a significant interaction between treatment and year at depths of 0.15 and 0.30 m.

Table 6. Effect of treatment and year on penetration resistance at four soil depths.

	Cone Penetration Resistance in MPa			
Depth (m)	**0.05**	**0.15**	**0.30**	**0.45**
Control	0.58 a	0.91 a	1.20 a	2.56
Early-dry	0.76 ab	1.47 b	1.89 b	2.52
Early-wet	0.92 b	1.46 b	1.69 bc	2.66
Late-dry	0.86 b	1.37 b	1.53 c	2.52
Late-wet	0.89 b	1.43 b	1.65 c	2.42
2010	0.76	1.16 a	1.35 a	2.56
2011	0.85	1.50 b	1.80 b	2.51
Interaction	ns	s	s	ns

Note: Means within each column followed by the same letter are not significantly different. (s = significant; ns = non-significant).

Bulk density was significantly higher in all trafficked treatments when compared with the control at depths centred at 0.02, 0.15 and 0.30 m (Table 7), however; there was no significant difference in BD values between trafficked treatments. Bulk density was significantly higher in 2011 when compared with 2010 at depths centred at 0.02 and 0.15 m.

Table 7. Effect of treatment and year on bulk density at four soil depths.

	Bulk Density (g cm^3)			
Depth (m)	**0.00–0.04**	**0.15**	**0.30**	**0.45**
Control	1.28 a	1.32 a	1.35 a	1.57
Early-dry	1.37 b	1.39 b	1.46 b	1.62
Early-wet	1.39 b	1.40 b	1.47 b	1.59
Late-dry	1.35 b	1.43 b	1.48 b	1.54
Late-wet	1.37 b	1.40 b	1.47 b	1.58
2010	1.33 a	1.37 a	1.43	1.61
2011	1.37 b	1.40 b	1.46	1.55
Interaction	ns	ns	ns	ns

Means within each column followed by the same letter are not significantly different. (ns = non-significant).

Water infiltration rate (steady-state) was significantly lower (p = 0.001) in all trafficked treatments when compared with the control, however; there was no significant difference in IR between trafficked treatments.

4. Discussion

4.1. Soil Compaction

The results of this experiment show that annually repeated traffic in the baler harvest system in *Miscanthus* significantly increased soil compaction each year. Bulk density and water infiltration rate were significantly increased in all trafficked treatments when compared with the control, but there was no significant difference in compaction between the trafficked treatments even though treatments were applied at different soil water contents.

The soil water content (Table 4) data indicates soil at high water content, even though ground conditions appeared to be favourable and soil was dry at the soil surface in the early-dry and late-dry treatments. Therefore, in this experiment the water content in all trafficked treatments made the soil vulnerable to compaction when traffic was applied each year. This would support the findings of several authors [11,27–30] who have reported increased compaction attributable to high water content.

Also the adverse effects of high axle load on compaction have been reported by Duiker [31], Hakansson et al. [32] and Arvidsson [33], Alakukku [17], Botta et al. [34] and Tolon-Becerra et al. [16] reported on the negative effects of intensity of traffic on compaction while Hamza et al. [35] Forristal [36] and Schjønning et al. [37] reported on the negative effects of inflation pressure on compaction.

4.2. Crop Response

The effect of treatment on crop response is demonstrated in the results for trafficked zone stem numbers, biomass yield and overall stem yield. The reduced stem numbers and biomass yield in both late-traffic treatments when compared with both early-traffic treatments and the control are likely to be the result of cumulative effects of the annually repeated traffic on newly emerged shoots. This effect has also been reported in earlier related work [15].

The recovery in stem height in both late-traffic treatments when compared with both early-traffic treatments and the control was not unexpected as this occurrence had also been recorded in earlier related work [15]. It was observed that while the stem height in the late-traffic treatments recovered to almost match the values of the other treatments, stem diameter remained slender. Stems were stronger in the early-traffic treatments and weaker in the late-traffic treatments. It is expected, with regard to stem height in *Miscanthus*, that the plant's requirement for sunlight was a major influence, and consequently, the majority of stems elongated to similar height and the crop canopy became more uniform as the growing season progressed [15].

Early traffic significantly suppressed stem yield in trafficked zones even though new growth had not begun in the rhizomes. It is likely that the reduced stem yields in the early-traffic treatments, when compared with the control, were caused by a combination of the adverse effects of increased compaction on crop regrowth and/or internal rhizome damage caused by harvest machinery. These results would support the findings of several authors. Such as: Soane et al. [11], Alakukku et al. [38], Souch et al. [18], Hamza et al. [35], and Raper [39], who all reported harmful effects on crop production attributable to soil compaction although this is the first report of the adverse effects of compaction on the growth of *Miscanthus*. The reduced overall stem yields in the late-traffic treatments when compared with the early-traffic treatments are likely to have been caused by mechanical damage to the newly emerged shoots by harvest machinery. This effect has been reported previously in *Miscanthus* by Lewandowski et al. [8] and El Bassam et al. [7]. Furthermore, earlier work by O'Flynn et al. [15] attributed yield losses of 1.8 tdm ha^{-1} to the negative effects of *Miscanthus* harvest traffic operating at high inflation pressures in crops where new shoots had emerged.

The effect of traffic on crop response is demonstrated by results for trafficked zone stem numbers and biomass yield. Stem numbers in both late-traffic treatments in 2011 were approximately 10 stems m^{-2} lower than in those treatments in 2010 (Figure 2a,b), while values in both early-traffic treatments and the control remained virtually unchanged; this is likely the result of the cumulative effects of trafficking on newly emerged shoots in consecutive years. The reduced biomass yield in 2011 compared with 2010 was likely the result of a combination of increased soil compaction/rhizome damage and cumulative effects of damaged new shoots in consecutive years. Overall stem yield increased somewhat in 2011 when compared with 2010 even though the trafficked zone biomass yield was significantly reduced. This occurrence was also recorded in earlier related work [9,15]. It is likely that the increased rainfall in 2011, when compared with 2010 (Table 2), coupled with the expanding rhizome mat in the establishing crop were contributing factors.

European experiments have shown that biomass yields harvested in winter (November/December) ranged between 7 and 26 tdm ha^{-1} following the third growing season [40] with the highest non-irrigated yields (northern Europe) ranging from 15 to 19 tdm ha^{-1}. The biomass yields in the trafficked treatments of this experiment ranged from 14.6 to 20.3 tdm ha^{-1}, which compare favourably to the yields recorded in those non-irrigated, northern European crops, reported on by Clifton-Brown et al. [40].

Overall stem yield results compare poorly with results from Austrian experiments [40], which yielded between 14.1 and 18.7 tdm ha^{-1} when harvested in February. However, the results compare more favourably to results presented by Lewandowski et al. [41] that showed *Miscanthus* in the United Kingdom yielding between 9.2 and 12.7 tdm ha^{-1} when harvested in spring. As climatic conditions in Ireland are more comparable to those in the UK/northern Europe and the yield results are a reflection of this. It may be reasonable to assume that in similar climates the results of this experiment would also apply to other perennial crops, which produce new brittle shoots annually, that may be growing in alternative soil types.

4.3. Harvest Timing

Lewandowski et al. [8], and El Bassam et al. [7], suggested that the *Miscanthus* harvest should be completed before new season growth begins. O'Flynn et al. [9] added that all harvest operations should be completed before late March in northern Europe when the soil temperature reaches 10 °C (which activates new growth in the rhizomes) to prevent damage to all new growth, both underground and overground, by harvest equipment. Therefore, from this experiment *Miscanthus* should be harvested early, before the rhizomes have started to regrow as the magnitude of yield losses from compaction or other causes in early harvests is substantially lower than the yield losses, which can result from shoot damage in late harvest. Therefore, earlier harvests maximise yield by avoiding damage to new growth. Biomass losses during harvesting operations may also reduce yield, but such harvest losses have been shown to be unaffected by time of harvest [42] leaving the avoidance of damage to new growth to be the most important factor in minimising yield loss in *Miscanthus* harvests. The work of this study was conducted using the baler harvest system but should be applicable to any system used to harvest *Miscanthus*.

5. Conclusions

Growth and yield may be reduced after early (pre-shoot emergence) *Miscanthus* harvests, either due to compaction and/or physical damage to the rhizome network. Consequently, such effects should be minimised, where possible, by the avoidance of harvesting under conditions when soil compaction may occur and/or by choosing harvesting machinery options, which reduce the risk of soil compaction or physical rhizome damage. However, yield losses which may occur after early harvests can be expected to be substantially lower than those, which can be expected to occur following late (post shoot emergence) harvests as the magnitude of late harvest shoot damage exceeds that of other factors. The greatest factor in the minimisation of reductions in growth and yield after *Miscanthus* harvests is the avoidance of late harvest shoot damage.

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