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Effects of soil compaction and mechanical damage at harvest on growth and biomass production of short rotation coppice willow

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Abstract

The effects of soil compaction and mechanical damage to stools at harvesting on the growth and biomass production of short rotation coppice (SRC) of willow (*Salix viminalis* L.) were monitored on clay loam (CL) and sandy loam (SL) soils. Moderate compaction, more typical of current harvesting situations did not reduce biomass yields significantly. Even heavy compaction only reduced stem biomass production by about 12% overall; effects were statistically significant only in the first year of the experiment on sandy loam. Heavy compaction increased soil strength and bulk density down to 0.4 m depth and reduced soil available water and root growth locally. Soil loosening treatments designed to alleviate the effects of heavy compaction did not markedly improve the growth of willow on compacted plots. Hence the focus fell on harvesting. Extensive mechanical damage to stools caused a 9% and 21% reduction in stem dry mass on the clay loam and sandy loam soils as a result of fewer stems being produced. The particularly severe effect on the sandy loam soil probably resulted from a combination of dry conditions in the year of treatment, root damage and soil compaction under stools and might have been aggravated by the young age of the plants (1 year) at the time of treatment.

Keywords: Short rotation coppice; willow; harvesting; soil compaction; mechanical damage; biomass production

Introduction

European policy is to increase the proportion of electricity derived from renewable sources from 6 to 12% by 2010, in order to meet post-Kyoto targets of reducing greenhouse gas emissions. It is expected that energy crops, particularly willow (*Salix* spp) grown as short rotation coppice (SRC) and *Miscanthus* will make a major contribution to achieving these targets and this will require the planting of large areas of these crops across Europe.

SRC, a perennial crop which is expected to be in the ground for 20 to 30 years, is harvested in winter after the leaves have fallen, on a 2- to 3-year cycle. In Scandinavia, harvesting takes place when the soil is frozen but, in the UK and elsewhere in northern Europe, the harvest will frequently coincide with wet weather and high soil water contents (Wall and Deboys, 1997; Mitchell *et al*., 1999). Under these conditions, compaction, puddling and

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rutting are particularly likely given the high axle loads of SRC harvesters and associated machinery (Soane *et al*., 1981; Kofman and Spinelli, 1997). Apart from damaging the soil, rutting and loss of traction delays the harvesting operation, adds to costs and can result in sideways slippage of machinery, causing mechanical damage to stools.

The effects of soil compaction on plant growth are complex but reductions in yield have been reported in both temperate (Lipiec and Simota, 1994) and tropical (Kayombo and Lal, 1994) crops. This has frequently been attributed to mechanical impedance of root growth resulting in reduced water (Nambiar and Sands, 1992) and nutrient uptake (Alakukku and Elonen, 1995) or insufficient aeration (Liang *et al*. 1999, Lipiec and Simota, 1994). Water availability for crops might be further reduced by decreased infiltration (Soane and Ouwerkerk, 1995), resulting from the decline in hydraulic conductivity which generally accompanies compaction (Horton *et al*., 1994). Compaction also often results in reduced plant populations (Arvidsson and Håkansson, 1996) and the production of smaller, stunted plants with low light interception (Assaeed *et al*., 1990). Although most of these effects have been described for annual crops, trees also appear to be similarly affected, notwithstanding their deeper root system (Wronski and Murphy, 1994).

In perennial crops, however, there is little opportunity to reduce compaction by deep cultivation; wheelings can remain compacted for 30-40 years (Wronski and Murphy, 1994). The impacts of the compaction and mechanical damage that large machinery can cause in willow SRC systems have not been quantified. This paper describes the effects of soil compaction and mechanical damage at harvesting on soil properties, willow SRC growth and biomass production in two soil types. The effectiveness of soil loosening treatments is tested.

Methods

Sites, treatments and experimental design

Two trials were conducted on different soil types. The first was at Kettering, Northamptonshire (52°4' N, 0° 4' W) on clay loam overlying clay (Hanslope series) hereafter referred to as CL. The plantation was established in 1994 and consisted of 10 ha of a mixed-clonal planting of willow. Trees were planted in double rows spaced at 1.5 m between the rows, 0.9 m within the rows and 1 m along the rows, giving 8,330 plants ha^{-1}. A site survey in February 1997 showed that the *Salix viminalis* clone 'Q683' was the most uniform and so plots of this clone were demarcated for the trial. Each plot was 20 m long and consisted of two experimental double rows and two outer double guard rows. A randomised block experimental design was used in which six experimental treatments were replicated three times. Plots were initially harvested by hand to eliminate effects of harvesting damage, after which the experimental treatments were imposed (Table 1).

Table 1. Treatments imposed on willow SRC.

Treatment code	Treatment name	Description
T1	Control	No compaction and no mechanical damage to stools
T2	Moderate compaction	Three passes of a 7-tonne loader either side of each double row
T3	Heavy compaction	Three passes of a 7-tonne loader between and within each double row
T4	Mechanical damage	7-tonne loader driven over the cut stools
T5	General loosening	Heavy compaction followed by loosening using a high-lift, winged, subsoiling tine to 30 cm depth
T6	Localised loosening	Heavy compaction followed by loosening using a low-lift, winged, subsoiling tine with a cutting disc ahead of the tine leg to a depth of 30 cm

When compaction treatments were imposed the loader (Sanderson, 247TS Teleporter) was fitted with 16.9/14-28 and 12.5/80-18 tyres on front and rear wheels respectively, inflated to a pressure of 3 bars. The soil was relatively dry (21% volumetric water content) when the compaction treatments were applied. The basic features of the deep loosening tines were described by Spoor and Godwin (1978) as shown in Figure 1. In treatment T5, the wing lift height was 100 mm and the tine had a wide leading share (80 mm) while in treatment T6 wing lift height was 50 mm and the share width was 25 mm.

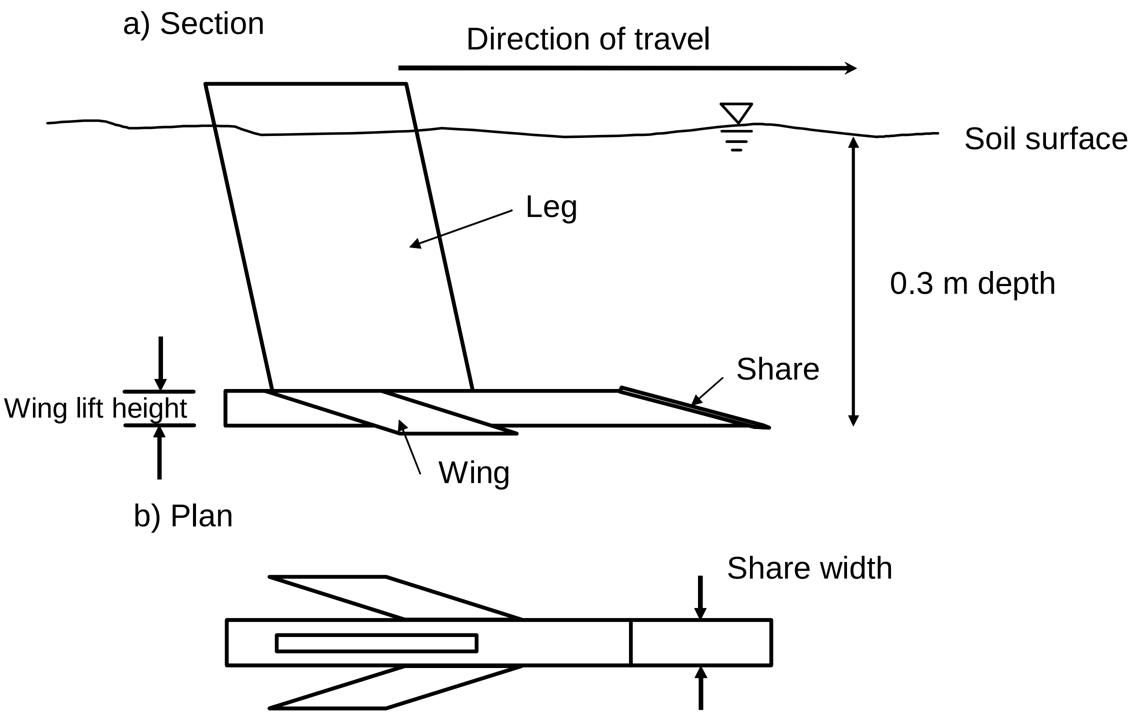

Figure 1. a) Section and b) plan view of a winged tine of the type used to loosen compacted soil. The tine is pulled through the soil behind a tractor.

In devising compaction treatments (T2 and T3), the primary concern was to produce a range of treatments differing in the severity of the compaction. They were not all intended to replicate on-farm harvesting conditions. Thus, T2 represents the type of loads which would often pass between double rows during harvesting whilst the compaction in treatment T3 is greater than would be expected to occur commercially. The two loosening treatments were included to see whether the effects of serious compaction, caused by the heavy traffic, could be mitigated.

The second trial at Silsoe, Bedfordshire (52° 2' N, 0° 2' W) was on sandy loam overlying sandy clay loam (Cottenham series) henceforth called SL. In February 1998, 0.2 m length cuttings of *Salix viminalis* ‘Q683’ were planted in a double row design at a spacing of 1.5 m between double rows, 0.8 m within the rows and 0.9 m along the rows giving 9,660 plants ha^{-1}. The trial was allowed to establish during 1998, during which irrigation was applied twice in August. It was then harvested by hand in late February 1999 and, using the same plot size and experimental design as at the CL site, the same six treatments were imposed in early March when the volumetric soil water content was high (32%). A combination of severe infestation by the Great Willow Aphid (*Tuberolachnus salignus* Gmelin) and water stress caused the complete defoliation and subsequent dieback of part of this experiment in September 1999 so that in the following year it proceeded with only two blocks and without the loosened treatments.

Soil measurements

At each site, soil pits were dug and samples collected from 0.1 m depth and then at 0.2 m intervals down to 0.9 m for analysis of soil particle size (6 samples) and water holding characteristics (3 samples). One year after imposing the treatments, pits were dug across the rows to a depth of 1 m to expose the root systems of four stools in compacted and control plots. Root profile maps were drawn, marking the ends of all visible roots on a large piece of clear plastic placed over the soil pit wall. Visual assessments of soil structure were also conducted to identify the main soil horizons and compaction zones. On the clay loam, root length density was determined from soil blocks (ranging from 0.002 to 0.008 m^3) taken at four depths in the profile (0.1 m, 0.2 m, 0.4 m and 0.75 m) to sample each horizon as well as the area immediately below the wheelings. Roots were then washed, separated, arranged on a Perspex tray and scanned. Length was determined from digital images using image analysis software (Delta-T Scan, Delta-T devices, Cambridge). Roots down to 0.08 mm diameter could be detected using this method.

Just before and after treatments were imposed, six measurements $plot^{-1}$ of soil strength between the double rows were made at 0.03 m depth intervals down to 0.45 m with a Bush SP500 penetrometer (Findlay, Irvine Ltd., Penicuik, Scotland).

Meteorological data

An automatic weather station (Skye Mini-met, Skye Instruments, Powys, Wales) was installed at the Kettering site and soil temperature, air temperature, relative humidity, solar radiation, wind speed and rainfall recorded hourly. Data from an existing automatic weather station (Cassella

Ltd., Kempston, Bedfordshire) located approximately 0.6 km from the Silsoe field trial were collected, and the same variables were recorded as at Kettering. Reference evapotranspiration (ET_o) was calculated for both sites using the Penman-Monteith combination equation as described by Smith (1991).

Plant measurements

In each experimental plot, five stools were chosen for measurements. Monthly counts were made of the number of stems stool^{-1} to determine stem density (number of stems m^{-2}), and the basal diameter of 15 of the stems on each stool was measured with digital calipers (Camlab, Cambridge). Stems from spare plots of 'Q683' were harvested at the end of each year to derive relationships between stem basal area (SBA) and stem dry mass. The relationships fitted were logarithmic forms of the power curve, $Y = a\,(SBA)^b$:

$$\ln y = \ln a + b \ln(SBA) \quad (1)$$

where Y is dry mass (g), a and b are constants and SBA is in cm^2. These relationships were used retrospectively to estimate stem dry matter from the stem diameter measurements. Stem dry mass ha^{-1} was calculated as the product of stem density ha^{-1} and average stem dry mass.

Leaf area index (LAI) and light interception were measured at monthly intervals with a SunScan system (Delta-T devices, Cambridge, UK). Fractional interception was interpolated between these dates and used to calculate the daily solar radiation intercepted by each plot. Seasonal radiation conversion ratios were determined for each treatment from the seasonal increments in stem dry mass ha^{-1} and seasonal solar radiation interception by the crop.

At harvest, areas 10 x 5 m at Kettering and 7.2 x 4.6 m at Silsoe were demarcated in the centre of each plot and within these areas all stools were cut by chain saw at 0.1 m above ground level. For each stool, the number of stems and fresh mass of all stems were recorded. Fresh mass was converted to dry mass using fresh:dry mass ratios, obtained from 1-2 kg samples of stems taken from each plot which were oven-dried at 100 °C to constant mass.

Data analysis

Data were analysed mainly by ANOVA using Genstat for Windows (NAG Ltd, Oxford) with a randomized block design. Where repeated measurements were made through the season, an ANOVA was performed on the data from each measurement occasion.

Results

Meteorological data

While Silsoe is generally dryer than Kettering and has a considerably higher ET_o (Table 2), the two sites have similar radiation and temperature regimes. At Silsoe, rainfall was particularly low and exceeded by ET_o in 1997 and 1999, the year when experimental treatments were imposed.

Table 2. Summary of March to November meteorological data for Kettering and Silsoe from 1997 to 2000.

Site	Year	Rainfall (mm)	Mean daily temperature (°C)	Mean daily solar radiation (MJ m^{-2} d^{-1})	ET_o (mm)
Kettering	1997	524	12.2	11.8	470
	1998	628	12.6	12.3	440
	1999	500	12.1	11.4	453
	2000	649	12.1	*	*
Silsoe	1997	364	12.8	*	602
	1998	631	11.7	11.1	556
	1999	408	12.0	13.9	560
	2000	662	12.6	11.7	492

*Data not available

Soil strength and compaction

In the clay loam, the volumetric water content for field capacity and permanent wilting point in the top 1 m were determined as 394 mm and 242 mm respectively, giving an available water content of 152 mm in the top 1 m. The values for the sandy loam were 330 mm and 188 mm, with an available water content of 142 mm in the top 1 m.

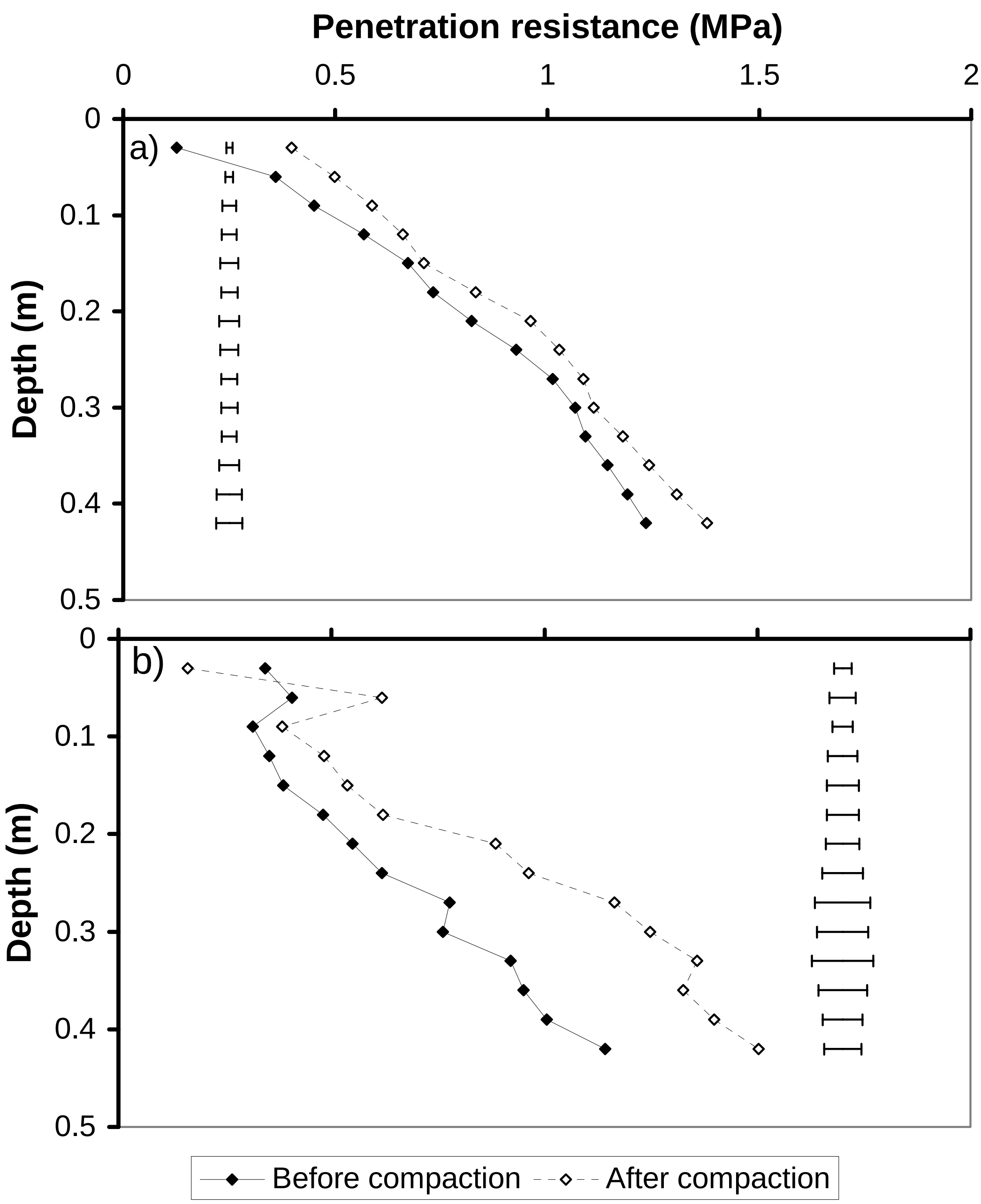

Figure 2. Soil penetration resistance in the heavy compaction treatment (T3) before and after compaction with a 7-tonne front-end loader in trials on (a) clay loam in 1997 and (b) sandy loam in 1999. Bars indicate the standard error of the difference between treatment means (3 df).

After compaction, the soil was significantly denser underneath the rutted areas as shown by the increased resistance to penetration (Figure 2), particularly in the sandy loam where the increase was 37 % on average. The soil dry bulk density increased from 1.35 g cm^{-3} in the control treatments to 1.65 g cm^{-3} in the compacted CL soil at 0.1 m depth. At Silsoe the values were 1.40 g cm^{-3} and 1.70 g cm^{-3} respectively. Heavy compaction reduced soil available water content at Kettering to 96 mm m^{-1} but at Silsoe it was increased slightly to 157 mm m^{-1}. Rut depths were 46 mm on average on the CL and 100 mm in the SL immediately after compaction treatments were imposed. The average rut depth decreased to 21 mm on the CL after three growing seasons and 68 mm on the SL after two, but at both sites, penetration resistance still remained higher in the compacted than in the control treatments.

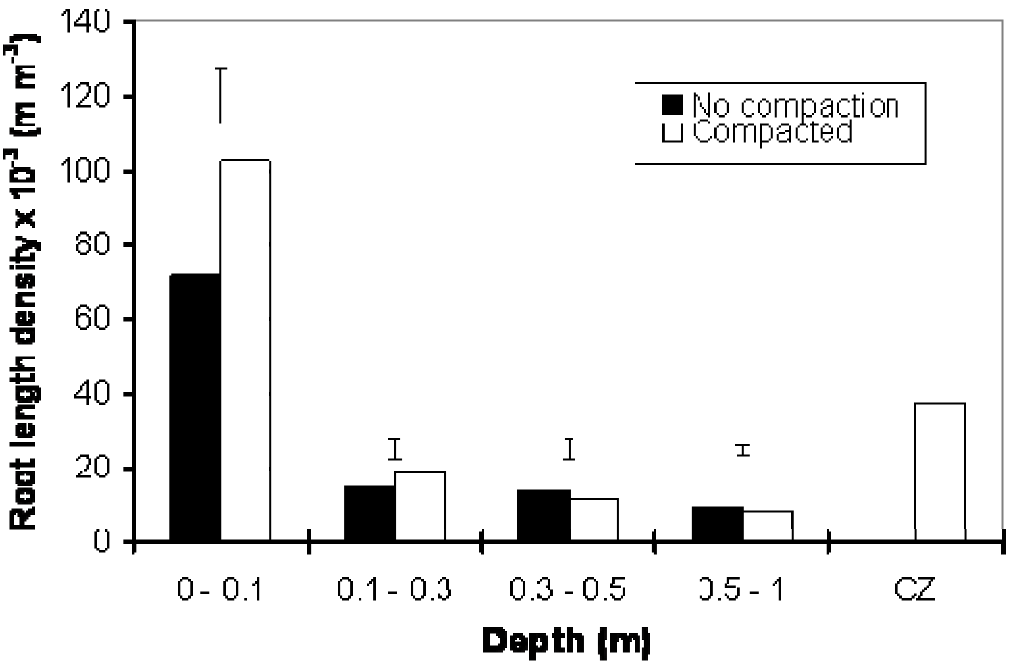

Figure 3. Root length density in the structural horizons identified in soil pits dug in clay loam in control and heavily compacted plots. Bars indicate the standard error of the difference between treatment means at each depth (6 df). For comparison, root length density in the compacted zone (CZ) of compacted plots is also shown.

In the CL, in both heavily compacted and control plots, the greatest root length density was found in the top 0.1 m of the soil profile (Figure 3) and was highest in compacted plots. Below 0.1 m, there was little difference between the treatments and roots were found down to 1.0 m. At both trial sites, U-shaped zones of compacted soil extending from the surface to about 0.4 m deep and about 0.3 m beyond each rut were evident in compacted plots. In these compacted zones in the CL, root length density was 14 % less than that from 0 to 0.3 m depth in the control treatment, suggesting that the consolidated nature of the material restricted root penetration and growth. In the surface soil surrounding these compacted areas, however, root length density was greater than the average value for the control treatment, suggesting compensation for the restricted development under the ruts. Root distribution maps also indicated reduced root numbers underneath ruts in the heavily compacted plots.

Canopy development and radiation interception

In the first year of growth after coppicing, the LAI of SRC had reached a maximum of 7 compared to around 4 on SL (Figure 4). Canopy development in the spring, however, was more rapid on SL so that the control treatment had a LAI of 2 by mid-May compared with about mid-June on CL. At both sites, the mechanical damage caused a smaller LAI than the control treatment through most of the season and this was as LAI approached its highest values in summer. By contrast, there were no significant differences between the control, compacted and loosening treatments. Trends in the second year were qualitatively similar.

With the exception of the mechanical damage treatment, similar amounts of solar radiation were intercepted by all treatments over each growing season (66 – 80%). On a sandy loam, SRC in the control, compacted and loosening treatments intercepted 73% of the incoming 3050 MJ m^{-2} of solar radiation but only 65% in the mechanical damage treatment.

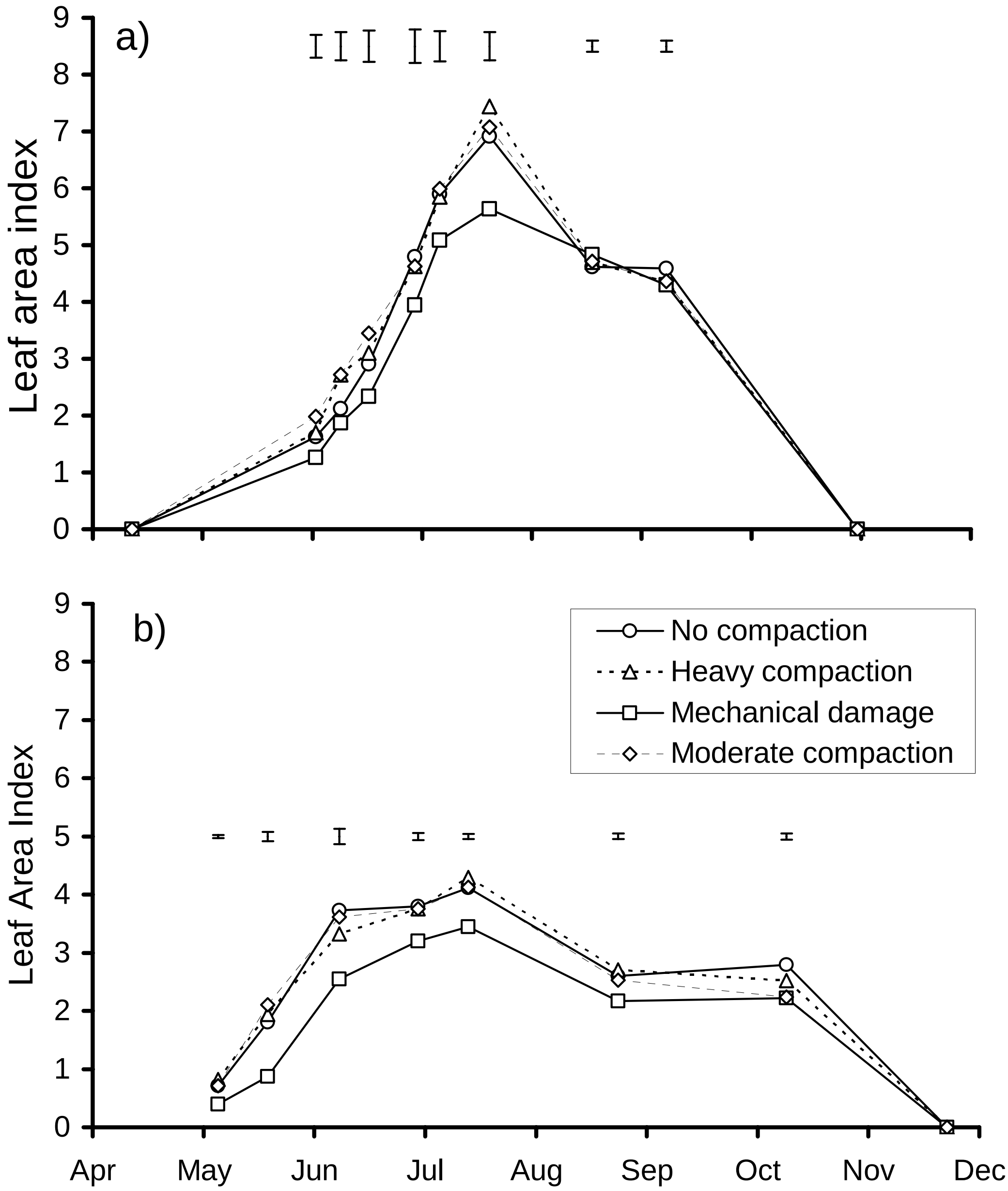

Figure 4. The effect of mechanical damage and compaction on the development of leaf area index in the first year after coppicing on a) clay loam and b) sandy loam. Bars indicate the standard error of the difference between treatment means (10 df).

Stem density and seasonal biomass production

In the early part of the first growing season, all plants growing on CL produced a large number of shoots as stools grew back after coppicing. Maximum stem density occurred in June of the first growing season (Figure 5a). This was then followed by considerable stem death and a period of reduction in stem density occurred annually between about June and August. In the control treatment in the first growing season, for example, stem density fell from 38.6 to 21.5 m^{-2}, a 44% reduction and by November 2000 it reached 12.7 m^{-2}, a 67% reduction from the maximum in 1997.

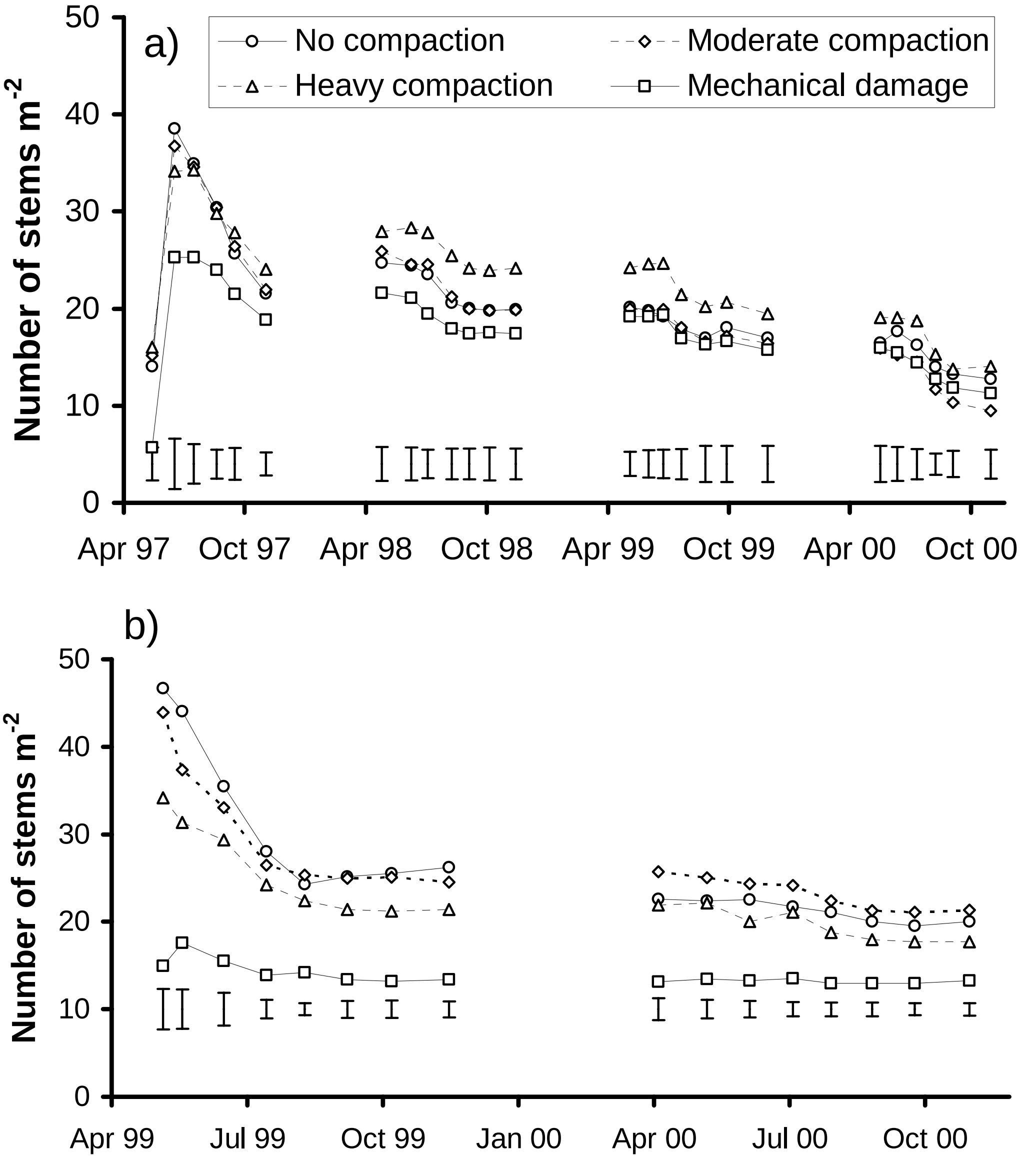

Figure 5. The effect of compaction and mechanical damage treatments on stem density on a) clay loam and b) sandy loam. Bars indicate the standard error of the difference between treatment means (10 d.f.; 3 d.f. for sandy loam during 2000).

Stem production on CL was very significantly reduced by mechanical damage and, in June 1997, was only 66% that of the control. However, stem survival was greater in SRC subjected to mechanical damage, particularly during the first growing season. The stem density in the other treatments fell proportionately more and, by November 2000, it was estimated that SRC that had been mechanically damaged had almost 90% of the number of stems in the control. A similar pattern of stem death was seen on SL (Figure 5b) so that in November 1999 and 2000, stem density in the control treatment was 56% and 43%, respectively of the maximum recorded in May 1999. Although the largest and most significant reduction in stem density was caused by the mechanical damage treatment, heavy compaction also resulted in significant reductions in the first year.

At neither site were there any stool deaths over the experimental period, even where they had been subjected to substantial mechanical damage so that the number of shoots stool^{-1} varied in the same way as the shoot density.

Long-term effects on biomass production

At the end of the first growing season on CL, there were no significant differences in estimated stem dry matter production between any of the treatments (Figure 6a) and biomass production was between 9 and 11 t ha^{-1}. At the end of the third growing season there were still no significant differences and standing stem dry matter was between 27 and 32 t ha^{-1}, indicating that mechanically damaged plants compensated for a reduced stem density by producing larger stems. From the second to fourth year there was a decline in stem dry mass from about July onwards which can be attributed to the death of stems. By the end of the rotation, there was considerable within plot variability on CL.

At the end of the first growing season on SL, stem biomass in the control treatment was 8 t ha^{-1} (Figure 6b). There were significant differences in stem biomass between the treatments on SL, with the heavy compaction treatment producing approximately 20 % less than the control treatment, and the mechanically damaged treatment 50 % less at only 4 t ha^{-1}. These differences were smaller in the second growing season and biomass production in all treatments was similar, at around 8 t ha^{-1} y^{-1}. Based on harvested yields, the average annual biomass production by the control treatments at the two sites was very similar, 8.3 t ha^{-1} on CL and 8.1 t ha^{-1} on SL.

Table 3 shows the effects of the experimental treatments on the components of yield at harvest when willow stems grown on CL and SL were 4 and 2 years old, respectively. The effects of compaction and soil loosening were not significant at either site. Even the heaviest compaction only reduced yields by 12% compared with the control sites. By contrast, mechanical damage to stools caused 9% and 21% reductions in total stem dry mass on CL and SL, respectively. Fewer stems m^{-2} and fewer stools ha^{-1} (on CL) contributed to smaller yields while mean stem dry weight on mechanically damaged plants was very similar to that of the control.

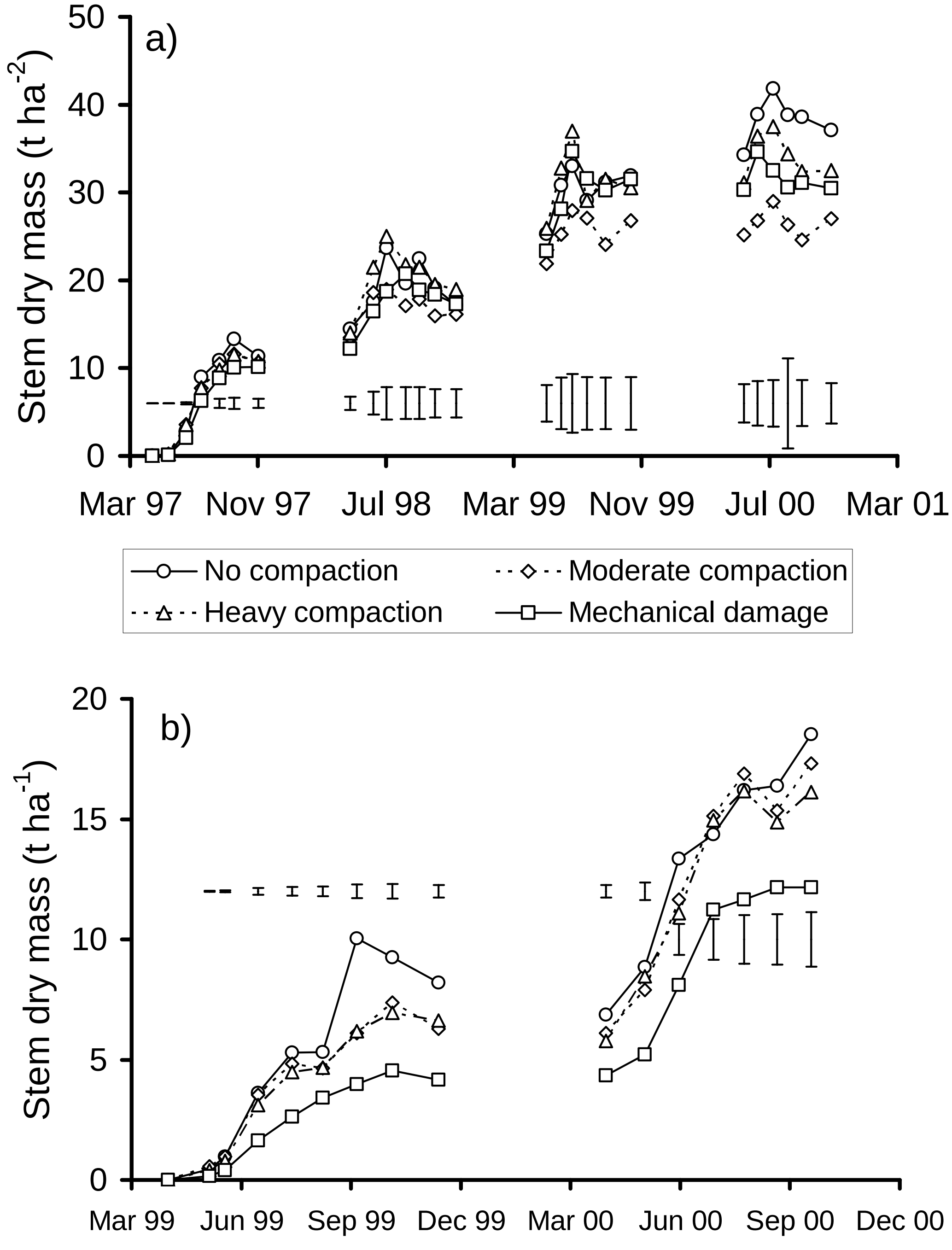

Figure 6. Stem biomass production estimated from stem density and diameter measurements on a) clay loam and b) sandy loam. Bars indicate the standard error of the difference between treatment means (10 d.f.; 3 d.f. for sandy loam during 2000).

The conversion ratio of solar radiation into stem biomass (using calculated values of radiation interception) was around 0.6 g MJ^{-1} in the first, 0.4 g MJ^{-1} in the second and 0.5 g MJ^{-1} in the third growing season on CL, with little difference between the treatments. In the first growing season on SL, the values were 0.4 g MJ^{-1} for the control plants, 0.3 g MJ^{-1} for plants on the heavily compacted soil and only 0.2 g MJ^{-1} for the mechanically damaged plants.

Table 3. Components of yield at harvest for Kettering in February and Silsoe in March 2001.

Trial and Treatment	Mean number of stools ha^{-1}	Mean number of stems m^{-2}	Total stem dry matter production (t ha^{-1})	Mean stem dry weight (g)
Kettering				
(1) Control	7770	15.0	33.4	225
(2) Moderate compaction	7960	16.1	32.0	199
(3) Heavy compaction	7770	16.8	29.5	176
(4) Mechanical damage	7380	13.3	30.5	230
(5) General loosening	7790	16.3	30.3	186
(6) Localised loosening	7530	16.0	30.6	191
s.e.d. (10 d.f.)	170	0.9	1.18	12.0
Silsoe				
(1) Control	9510	17.6	16.3	93
(2) Moderate compaction	9660	19.8	16.4	83
(3) Heavy compaction	9510	18.9	14.4	76
(4) Mechanical damage	9510	13.6	12.9	94
s.e.d. (3 d.f.)	204	2.14	1.59	6.1

Discussion

On both clay loam (CL) and sandy loam (SL), heavy soil compaction caused significant changes in soil characteristics, particularly increases in soil strength and dry bulk density and, on CL, a reduction in the water-holding capacity. Increases in soil strength were particularly marked on the sandy loam soil. The effects of compaction on soil structure were restricted, however, to 0.4 m beneath the wheelings. There was little root growth in this zone but compensatory growth occurred in the uncompacted topsoil. A similar response has been observed in pine (*Pinus radiata* D.Don) where roots avoided compact layers and proliferated in weaker zones (Nambiar and Sands, 1992).

The proportion of the root zone affected by compaction will depend on the proportion of the area trafficked and the depth of the root system. At the plant spacing used in these experiments and with a root depth of 0.5 m, root growth for the heavy and moderate compaction treatments would have been restricted by compaction to about 42% and 21%, respectively, of the rooting volume. Once the root system developed below the compacted layer the proportion of the root zone restricted would decline rapidly so that, by the time the roots reached 2 m depth, only 10% would be compacted even in the heavily compacted treatments. SRC will thus be most susceptible to compaction damage when it is very young or is growing on shallow soils. It also emphasises the need to alleviate any compaction if present in the main rooting zone before planting SRC.

On CL, non-destructive plant measurements through the duration of the experiment indicated that there were no significant long-term effects on growth or biomass production attributable to the compaction treatments. On SL, the effect of heavy compaction on biomass decreased from a 21% reduction at the end of the first growing season to be insignificant by the end of the second growing season.

The larger effect of heavy compaction on SL than on CL can be attributed to the following factors: the greater susceptibility of SL to compaction; the younger crop on SL, which had only established for one year compared with three on CL; and the higher evaporative demand at the SL site, which would have resulted in the plants experiencing greater water stress. The moderate compaction treatment on SL did not, however, have a significant effect on biomass production, confirming results from earlier research in the UK that also indicated that normal harvesting operations had no effect on willow yields (Forest Research, 1998). It is also likely that the development of an extensive root mat in willow SRC systems would help to protect the soil from compaction by providing mechanical support for vehicles. Root profile maps for the at showed that while roots could be found down to 1 m, most occurred in the top 0.3 m. This dense surface rooting habit has also been shown elsewhere with 40-45% of both fine root length and mass occurred within the top 0.1 m (Rytter and Hannson, 1996).

The traditional agricultural response to soil compaction is to alleviate it by subsoiling (Spoor and Godwin, 1978). In this experiment, however, there appeared to be no benefits of subsoiling, probably because of damage to plant roots.

In contrast to compaction, mechanical damage, caused by driving a 7 t front-loader over the stools, resulted in large and significant effects on plant growth, reducing stem density and LAI in the first year on both CL and SL soils. For example, there was a 50% reduction in stem dry mass at the end of the first year on SL. At the final harvests yield reductions of 9% and 21% occurred on CL and SL sites respectively. At both sites in the first year of the trial, control plants produced a large number of stems by June but 44% of these died by the end of the season. Stools subject to mechanical damage produced far fewer stems in the first year, but a smaller proportion of these died (26% at Kettering and 24% at Silsoe) compared with the control. This trend continued over succeeding years so that the difference in stem density between the two treatments grew less with time.

The high shoot mortality seen in control plants is not unusual in willow and three years after cutting can be as high as 90% (Ceulemans *et al*., 1996). Normally the shoots which die are small and contribute little to total biomass (Hytönen, 1995; Verwijst, 1991). As a result of stem death in the control treatment, there was little difference by the second year in LAI between the treatments on CL although differences still persisted on SL. These differences did not result in appreciably higher solar radiation interception by the control treatment in the second year, however, because a LAI of about 4.0 was sufficient to intercept about 90% of solar radiation. A similar level of radiation interception with a LAI of 4 was also found for both *Populus trichocarpa* and *Salix viminalis* by Cannell *et al*. (1988).

The main effect of mechanical damage on stem numbers appeared to be as a result of the above-ground damage to the stool, which caused a reduction in the number of buds. At the end of the first and second years, respectively, non-destructive measurements indicated that mechanical damage caused a 49% and 35% reduction in biomass on SL compared with 11% and 0% on CL. The different response to mechanical damage at the two sites can be attributed to several factors. First, in the year of treatment (1997 at Kettering [CL] and 1999 at Silsoe[SL]), seasonal rainfall was almost 120 mm less at the SL site than at the CL site. The evaporative demand on the SL site was 20% greater, therefore inducing more water stress than on the CL site. Second, the SRC on SL was younger than that on CL (1 compared with 3 years old) so that its root system would have been much shallower. Several other studies have indicated that the effects of compaction on plant growth interact with water stress (Liang *et al*. 1999) and diminished or not detectable in loose soil (Miller *et al*., 1996; Quesnel and Curran, 2000). The profiles of soil strength showed a bigger difference between the control and heavy compaction of the SL site, suggesting greater compaction at depth.

In spite of the differences in climate, soil and duration of the experiments on CL and SL, harvested stem biomass from the control treatments averaged over years was very similar (8.1 t ha^{-1} yr^{-1} on SL and 8.3 t ha^{-1} yr^{-1} on CL) and comparable to the average of 8.1 t ha^{-1} yr^{-1} estimated for willow trials in the UK by Mitchell *et al*. (1999).

In conclusion, this study has demonstrated that if soil compaction can be avoided in the first years after planting then it is unlikely to have a major impact on biomass yield once the root system is well established. Furthermore, willow SRC appears to be able to compensate for extensive mechanical damage to stools through better stem survival rates over the period of the coppice cycle.

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