Bioresource Technology, Volume 97, Issue 3, February 2006, Pages 437-448

Published in Bioresource Technology: doi:10.1016/j.biortech.2005.03.003

Willow growth in response to nutrients and moisture on a clay landfill cap soil. I Growth and biomass production

PETER J. MARTIN[§] AND WILLIAM STEPHENS*[1]

[§] *Agronomy Institute, Orkney College, Kirkwall, Orkney, Scotland KW15 1LX*

**Institute of Water and Environment, Cranfield University, Silsoe, Bedfordshire MK45 4DT, UK*

Abstract

This paper describes studies into the effect of soil factors and water stress on the growth and biomass production of willow (*Salix viminalis* L.) on a clay landfill cap soil. Individual plants were grown in lysimeters containing Oxford clay and using different soil amendments, bulk densities and watering regimes. Three years from planting, stem biomass production in well-watered plants was least (0.28 kg plant^{-1}) with high bulk density soil (1480 kg m^{-3}) and no nutritional amendment but was increased 10-fold (2.53 kg plant^{-1}) by reducing soil bulk density (1200 kg m^{-3}) and adding thermally dried sewage sludge and fertilisers (N, P and K). This was low, however, compared with production on a sandy loam soil (6.23 kg plant^{-1}) with the same amendments and a similar bulk density. These large treatment differences were also reflected in number of stems plant^{-1}, stem basal area plant^{-1} and plant leaf area. Plants growing on the Oxford clay had higher root:stem ratios than those on the sandy loam. Water stress reduced stem biomass production by 26 - 37% and caused higher root:stem ratios. Foliar and soil analyses and pot trials indicated that the effects of the soil amendments could be attributed to the addition of N and P which are low in Oxford clay. The research suggests that reasonable biomass production from willow SRC on Oxford clay landfill caps will be dependent on the application of nutritional amendment to the soil at these sites.

Keywords: lysimeters, *Salix viminalis,* short-rotation coppice, landfill cap soil

1 Introduction

Restoration of landfill sites to an acceptable after-use is a fundamental aspect of their post-closure management. In the past, restoration to agriculture was a priority but other options are now being considered (Dobson and Moffat, 1993a; McRae, 1998). With about 28,000 ha of landfill sites in England and Wales (Environment Agency, 2004), planting energy crops on restored sites offers the waste disposal industry a potentially valuable, environmentally beneficial and sustainable use of restored sites (Nixon et al. 2001). The biomass could be used for electricity generation, the production of charcoal or simply as a carbon sink. Currently in the UK, the most widely planted energy crop is willow (*Salix* spp), grown as short rotation coppice (SRC). By adding large amounts of organic matter to the soil as root and leaf material (McElroy and Dawson, 1986; Zan et al. 2001), SRC could also be important in upgrading poor restoration cap soils and there are several references to the planting of SRC on such sites (Ettala, 1988; Moffat and Houston, 1991; Alker et al., 2002).

Landfill sites are often established on impermeable clay soils because these prevent the seepage of landfill leachate. In the UK, several large sites, receiving municipal household waste from London, have been sited on Oxford clay (Batchelder et al., 1998). Although the

[1] Corresponding author. Tel. +44 (0) 1525 863296
Fax. +44 (0) 1525 863344
e-mail: w.stephens@cranfield.ac.uk

potential production from SRC in southern England has been estimated at up to 20 t ha^{-1} of dry stem wood annually (Cannell et al., 1987), this is likely to be reduced on Oxford clay landfill sites by a number of factors (Nixon et al., 2001). The most important of these is the use of Oxford clay for constructing the restoration cap into which the SRC would have to be planted. Like other clay soil forming materials, Oxford clay is low in nutrients and organic matter and because of its texture it drains poorly and readily becomes waterlogged and anaerobic (Bending et al., 1999; Dobson and Moffat, 1993a). These properties are compounded by soil compaction while the restoration cap is being laid which reduces soil pore space, aeration, water-holding capacity and root penetration. Reserves of soil water will be further restricted on most landfill caps because soil depth is seldom more than 1 m while at least 1.5 m is required for good tree growth (Bending and Moffat, 1997a; Stephens et al. 2001). This situation will be aggravated at Oxford clay landfill sites which are located in parts of the UK with low rainfall.

There have been a number of papers presenting qualitative descriptions of the effects of poor soil conditions on the establishment and growth of SRC on landfill sites. However, Nixon et al. (2001) highlighted the lack of quantification of the effects of water availability and poor soil conditions typical of those on restored landfills on biomass production and its allocation within willow SRC. The objectives of the research described in this and a following paper were therefore to quantify the effects of nutrients, soil bulk density and water availability on the potential biomass production and assimilate partitioning of willow grown as SRC on Oxford clay.

2 Methods

2.1 Site and lysimeters

All the research was undertaken at Cranfield University Silsoe, Bedfordshire, UK (52 °N, 0.3 °W, at 60 m altitude). Cylindrical polyethylene lysimeters, 0.54 m in diameter and 0.9 m deep, were each fitted with a drainage tap at the base and then filled with 0.1 m of gravel and a 0.7 m depth of soil. After filling, lysimeters were placed on wooden palettes and arranged on a 2 m square spacing. In 2001, the spacing between lysimeters was increased to 4 m to prevent plants shading each other. The experiment was surrounded by a single guard row of lysimeters. Individual willow cuttings (*S. viminalis* 'Jorr') were planted in each lysimeter on 21 April 1999 and all plants were coppiced in November 1999.

2.2 Treatments

Four soil treatments (Table 1) were investigated and differed according to type of soil, bulk density in the top 0.4 m and amendment used. Treatments were selected to simulate i) typical compacted cap soil (S1); ii) cap soil cultivated to reduce its bulk density (S2) and iii) cultivated cap soil improved by the addition of organic matter and fertiliser (S3). For comparison with better growing conditions, a sandy loam agricultural soil (S4) was included using the same amendments and a similar bulk density to S3. Oxford clay was obtained from Brogborough landfill site and the sandy loam soil came from Silsoe campus farm (Cottenham series). Different bulk densities were obtained by packing appropriate weights of soil of known bulk density into successive 0.1 m horizons. In treatments S3 and S4, Biogran (Swiss Combi Technology), a soil conditioner manufactured from thermally dried sewage sludge, was used as a source of organic matter. This product contains about 50% organic matter, 3.3% total nitrogen, 4.4% total phosphorous (as P_2O_5) and 0.2% potassium (as K_2O). It was mixed into the top 0.1 to 0.4 m of soil in the lysimeters at a rate equivalent to 200 t ha^{-1}. Although this is a higher rate than the 50-100 t/ha currently used at reclamation sites, the rate was

selected because Forest Research trials on reclaimed colliery waste in South Wales had shown improved growth by broad-leaved trees with rates of Biogran up to 200 t/ha (Bending and Moffat, 1997b). In 1999 and 2000, nitrogen was applied to treatments S3 and S4 at a rate of 200 kg N ha^{-1}. In 2001, 300 kg N ha^{-1}, 150 kg P ha^{-1} and 90 kg K ha^{-1} were applied to treatments S2, S3 and S4. Rates were increased in 2001 because leaf analyses in August 2000 showed that foliar levels of N and P in the amended treatments were low. The application to the S2 treatment was made to see whether this would improve its growth relative to S1 because, by the end of 2000, plant growth measurements showed only a small, non-significant, difference in growth between plants in the two treatments.

Table 1. Description of soil treatments used in lysimeters.

Treatment	Type of soil	Bulk density from 0-0.4 m (kg m^{-3})	Amendments
S1	Oxford clay	1480	None
S2	Oxford clay	1270	None
S3	Oxford clay	1200	Organic matter and fertiliser
S4	Sandy loam	1270	Organic matter and fertiliser

In the lysimeters, soil water at several depths was measured on most days of the growing seasons with time domain reflectometry probes (Moisture Point MP-917, Environmental Sensors Inc.) in 1999 and 2000 and by a Diviner (Sentek Pty Ltd) capacitance probe in 2001. Throughout the first year, all plants were watered frequently to ensure good establishment. In the second and third years, one plant per replicate in each soil treatment continued to be grown without water stress while the other was subjected to cycles of stress by allowing the soil water content to drop to wilting point before re-watering to saturation. Wilting point was determined visually as the point when the majority of leaves on a plant started to droop. The first visual indication of wilting was usually drooping of the growing points of leading shoots. Soil probes indicated that wilting occurred at a volumetric soil water content (θ_v), at 0.1 m depth, of about 30% in the clay treatments and 22% in the sandy loam. In 2000, plants were watered on the day that wilting occurred while in 2001, watering was on the third day of wilting. A more protracted period of stress was used in 2001 because estimates of stem dry matter at the end of 2000 indicated that the water stress treatment was having only a small effect on biomass accumulation. In the unstressed treatment, a soil water content corresponding to a soil water potential of -0.05 MPa in the top 0.10 - 0.15 m was used as the threshold for watering. These were identified from soil water release curves as corresponding to a θ_v of 47% for the clay and 27% for the sandy loam. Rainwater could not be prevented from entering the lysimeters and so the imposition of drought treatments was dependent on the occurrence of dry periods of weather. In figures and tables the two watering treatments are referred to as NS (no stress) and S (stress).

The experiment used a randomised complete block design with three replicates. In each replicate, one of the 8 treatments (4 soils x 2 watering regimes) was allocated to each lysimeter but since no water stress treatment was applied in the first year, each soil treatment was represented by two lysimeters per replicate in this year. In the second and third years, each replicate contained a single lysimeter with each treatment. The water stress treatment was applied to the same lysimeters in 2001 as in 2000.

2.3 Measurements

During the growing seasons, the basal diameters of all stems were measured monthly with digital calipers (Camlab, Cambridge) and converted to stem basal area (SBA), assuming the stem cross-section was circular. Plant SBA was calculated as the sum of the SBA of all the stems on a plant. Stem dry mass was determined from allometric relationships between this and SBA using 80 stems in 1999 after coppicing and 240 (10 per plant) in 2001. Stems were selected across the range of stem diameters and oven-dried at 105°C until constant mass. The relationships fitted were logarithmic forms of the power curve, $Y = a(SBA)^b$:

$$\mathrm{Ln}Y = \mathrm{Ln}a + b\mathrm{Ln}(SBA) \quad (1)$$

where Y is dry mass (g) and SBA is in cm^2. These relationships were then used to retrospectively estimate stem dry mass for all stems on plants.

In 1999, the same relationships were used for all treatments and these accounted for 99% of the variation in stem dry mass. In 2001, significant differences in the relationships were found between soil and watering treatments. In addition, there were significant differences between stressed trees in each soil treatment. For these, therefore, different relationships were used for each tree. For unstressed trees, the same relationship was used for the three trees in each soil treatment. On average, the relationships accounted for 98% of the variation in stem dry mass.

During the 2000 and 2001 growing seasons, non-destructive monthly measurements of leaf area were made to derive relationships between stem basal area and stem leaf area. Measurements were made on six stems of plants in each treatment using stems across the range of stem diameters. Stem leaf area was calculated from the product of number of leaves $stem^{-1}$ and an estimate of the average area of a leaf on each stem which was obtained from leaf area measurements made on every tenth leaf of sampled stems. Leaf area was derived from measurements of leaf length (from the base of the lamina to the tip) and width (at the widest point) using a linear relationship determined in 2000 from a sample of 30 leaves of different sizes:

$$A = 0.729\ (L\ W) \quad (2)$$

where A is area (cm^2), L is length (cm) and W is width (cm; s.e. of the regression coefficient, 0.014; $r^2 = 0.96$). Simple linear regressions were used for the relationships between SBA and stem leaf area. Significant differences were found in the relationship between soil and water stress treatments and measurement dates so that a different relationship was used for each treatment at each date. Averaged over treatment and measurement date, the relationships accounted for 85% and 80% of the variation in stem leaf area in 2000 and 2001, respectively. Generally, the highest correlations occurred from July to September when leaf areas were largest.

Plant leaf area duration (LAD) was calculated as the sum of each plant's leaf area on each day of the growing season. It was assumed that there was a linear change in leaf area between measurement dates.

At the final harvest in November 2001, all stems were removed from stumps by cutting them at their base. The lysimeters were then cut open and stumps were separated from roots. Stumps were defined as the above-ground part of the plant remaining after stem removal plus the below-ground part which had grown radially outwards from the original willow cutting. Roots were separated from stumps at the point where they emerged from the stump. Examination of guard row plants showed a fairly uniform radial distribution of roots and in experimental lysimeters, a sample, consisting of a one-quarter longitudinal section of soil core, was used to measure root biomass. This was randomly selected (but always excluded the

portion containing the Diviner access tube) and was divided into four segments, each of 0.2 m depth. These were left to soak in water for 48 h, and coarse roots (>2 mm diameter) were then washed out. Fine roots (<2 mm diameter) were sampled from the remainder of the soil core using soil density rings (20 mm deep by 54 mm in diameter) but particularly high concentrations occurred just below the soil surface and around the outside of the soil core. These were sampled by collecting one sample from the surface, mid-way between the willow stump and the edge of the soil core, and peripheral samples from the outer face of the soil core at 0.10, 0.30, 0.50 and 0.65 m depths. Fine roots washed from these samples were used to estimate the mass of fine roots in the upper and outer 0.02 m of the soil core. An estimate of the mass of fine roots in the remainder of the soil core was obtained by taking single soil samples mid-way between the willow stump and the edge of the soil core at 0.05, 0.15, 0.25, 0.35, 0.45, 0.55 and 0.65 m depths.

Soil density rings could not be used to sample the gravel at the bottom of the lysimeters (0.70 - 0.80 m depth) and so gravel was separated from soil in the 0.60 - 0.80 m soil segment and both fine and coarse roots were washed out and separated. No distinction was made between living and dead roots. Roots were oven-dried at 80 °C until constant mass. Table 2 shows how the location and depth of the fine root samples relates to the 0.20 m depth intervals used for presenting results.

Table 2. Location and depth of fine root soil samples in relation to the depth intervals used for presenting results.

Depth interval (m)	Depth of internal samples[a] (m)	Depth of peripheral samples[a] (m)
0-0.20	0 (0-0.02)[b] 0.05 (0.02-0.10) 0.15 (0.10-0.20)	0.10 (0-0.20)[b]
0.20-0.40	0.25 (0.20-0.30) 0.35 (0.30-0.40)	0.30 (0.20-0.40)
0.40-0.60	0.45 (0.40-0.50) 0.55 (0.50-0.60)	0.50 (0.40-0.60)
0.60-0.80	0.65 (0.60-0.70)	0.65 (0.60-0.70)
	Fine roots washed out of gravel at 0.70-0.80 m depth	

[a] Internal samples were used to calculate the mass of fine roots from the centre of the lysimeter to a radius of 0.52 m while peripheral samples were used to calculate the mass in the outer 0.02 m of the soil core.

[b] Figures in brackets indicate the depth interval over which each sample was used to calculate the mass of fine root.

Root:stem ratios have been calculated from the estimated dry weights of roots (coarse and fine) and stems (but excluding the stump).

Composite leaf samples from all lysimeters in each treatment were collected in August 2000 and 2001. Similar composite soil samples were collected from all lysimeters at 0.10 m depth in August 2000 and 0.30 m depth in November 2001. Soil and leaf samples from each treatment were analysed for nitrogen, phosphorus and potassium using methods described in MAFF (1986). Values presented for each element are the means of three determinations on different sub-samples from each composite sample.

2.4 Pot experiment

The effect of macronutrients on biomass production by willow on Oxford clay was investigated by a pot experiment established in 2001. The 8 fertiliser treatments consisted of a factorial arrangement of two levels (present or absent) of each of nitrogen, phosphorus and potassium. Fertilisers were applied as ammonium nitrate, single superphosphate and sulphate of potash at rates corresponding to 200kg N ha^{-1}, 100 kg P ha^{-1} and 60 kg K ha^{-1}, based on pot soil surface area. These rates were chosen because they were approximately two thirds of those applied to the lysimeters in 2001 and lower rates were considered more appropriate for young plants. Individual willow cuttings of the *S. viminalis* clone Q683 were planted on 5th April, in plastic pots 0.25 m in diameter and 0.22 m tall, filled with Oxford clay. Pots were placed on saucers to prevent roots growing into the soil. Fertiliser treatments were applied as top dressings to the pots after watering, one month after the cuttings sprouted. Until plants were harvested in mid-July, pots were watered daily, unless there was rain. At harvest, all shoots were removed from plants and their lengths measured. The shoots from each plant were then divided into three components: main shoot stem, main shoot leaf and other shoots (leaves and stems together). The three components were dried and weighed separately (at 100^{o}C until constant weight) and the proportion of main shoot dry mass in stem and leaf was then used to estimate the mass of these components in the other shoots, thereby allowing an estimate to be made of the dry mass partitioned between stem and leaf in each plant.

A randomised complete block experimental design was used with each treatment being applied to one of the eight pots in each of the four replicates.

2.5 Data analysis

Data were analysed using Genstat 5 – Release 4.1 (NAG Ltd, Oxford). Measurements from the lysimeter experiment in 1999 were analysed using a one-way ANOVA in randomised blocks while a two-way ANOVA in randomised blocks was used for the 2000 and 2001 measurements. Where repeated measurements were made through a season or over several seasons, separate ANOVAs were performed on the data from each measurement occasion. The pot experiment (section 2.4) was analysed by general analysis of variance. For both experiments, the statistical significance of main effects was determined from F ratios in the ANOVA table while that between treatment pairs was tested with the Student *t*-test using the appropriate standard error of the difference between means. A 5% significance level was adopted for identifying significant treatment effects.

3 Results

3.1 Climate

Figure 1 shows monthly rainfall and monthly average daily solar radiation and temperature at the Silsoe meteorological site over the 3 years of the trial. In the two growing seasons when water stress treatments were imposed, rainfall was only low in June and August 2000 and June 2001. Nevertheless, the irregular distribution of rain within months meant that it was still possible to impose 11 cycles of soil drying on the S3 and S4 treatments in 2000 and six in 2001. Fewer cycles were experienced by plants in the S1 and S2 treatments because their slow rate of water use, resulting from their smaller leaf area, meant that drying cycles were more often interrupted by rain.

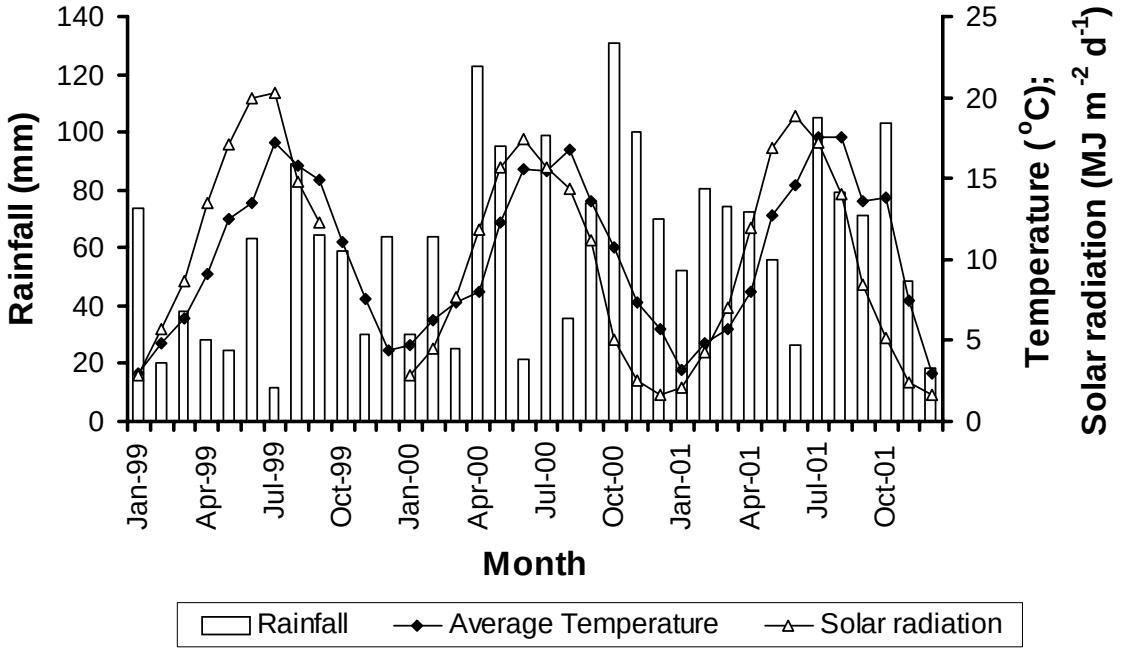

Figure 1. Monthly rainfall and monthly average daily temperature and solar radiation at Silsoe, Bedfordshire from January 1999 to December 2001.

3.2 Plant growth

With the exception of number of stems plant^{-1} at the end of 1999, there were large treatment differences at the end of each growing season in number of stems plant^{-1} and SBA plant^{-1} (Figure **3**). Generally, the two variables were significantly and similarly affected by the soil treatments. This resulted in growth being poorest during 1999 and 2000 in the unamended clay treatments (S1 and S2) and most vigorous in the sandy loam (S4); growth in the amended clay treatment (S3) was significantly better than in the unamended treatments but poorer than in the sandy loam. This trend continued in 2001 but the addition of fertiliser to the S2 treatment resulted in improved growth and a significantly higher SBA plant^{-1} than the S1 treatment. Water stress significantly reduced SBA plant^{-1} in 2001.

Plant leaf area was significantly affected by soil treatments in both 2000 and 2001 but by water stress only in 2001 (Figure 2). Thus, in 2000, the maximum in the sandy loam treatment (S4) was more than twice that of the amended clay treatment (S3) which in turn was about five times that of the unamended clay treatments (S1 and S2). In 2001, the leaf area of plants in all treatments, except S1, was greater than in 2000 and from June there were significant main effects of both soil and water stress and a significant interaction between the two. Throughout the season, soil treatments showed the same ranking for plant leaf area as occurred in 2000 except that it was significantly greater in the S2 than in the S1 treatment. The more protracted water stress regime used in 2001 resulted in greater leaf-fall after wilting than in 2000 and hence significant reductions in leaf area in all treatments except S1 - this resulted in a significant interaction between stress and soil treatments.

Table 3. The effect of soil and water stress treatments on number of stems plant-1 and SBA plant-1 measured in November 1999, 2000 and 2001 at the end of each growing season. The top part of the table shows treatment means and the bottom part shows the significance of treatment main effects and interactions.

Treatment	Number of stems plant^{-1}			SBA plant^{-1} (cm^2)		
	1999	2000	2001	1999	2000	2001
S1, NS	3.7	12.0	12.0	1.4	5.7	6.5
S1, S[a]	-----	12.0	12.0	-----	4.9	5.4
S2, NS	4.0	14.3	15.3	1.7	7.1	20.4
S2, S[a]	-----	11.7	11.7	-----	6.6	14.5
S3, NS	3.2	21.3	21.0	6.5	27.9	46.5
S3, S[a]	-----	23.3	22.3	-----	25.9	38.0
S4, NS	4.2	26.3	25.7	13.6	49.9	84.5
S4, S[2]	-----	35.7	33.0	-----	53.5	77.7
df	18	14	14	18	14	14
SED[b]	0.8	3.4	3.0	0.9	2.2	2.6
Probability levels of F ratios for treatment main effects and interactions						
Soil	0.610	<0.001	<0.001	<0.001	<0.001	<0.001
Water stress[a]	-----	0.222	0.422	-----	0.954	<0.001
Soil x stress	-----	0.122	0.123	-----	0.312	0.246

[a] There was no water stress treatment in 1999.

[b] Standard error of the difference between treatment means.

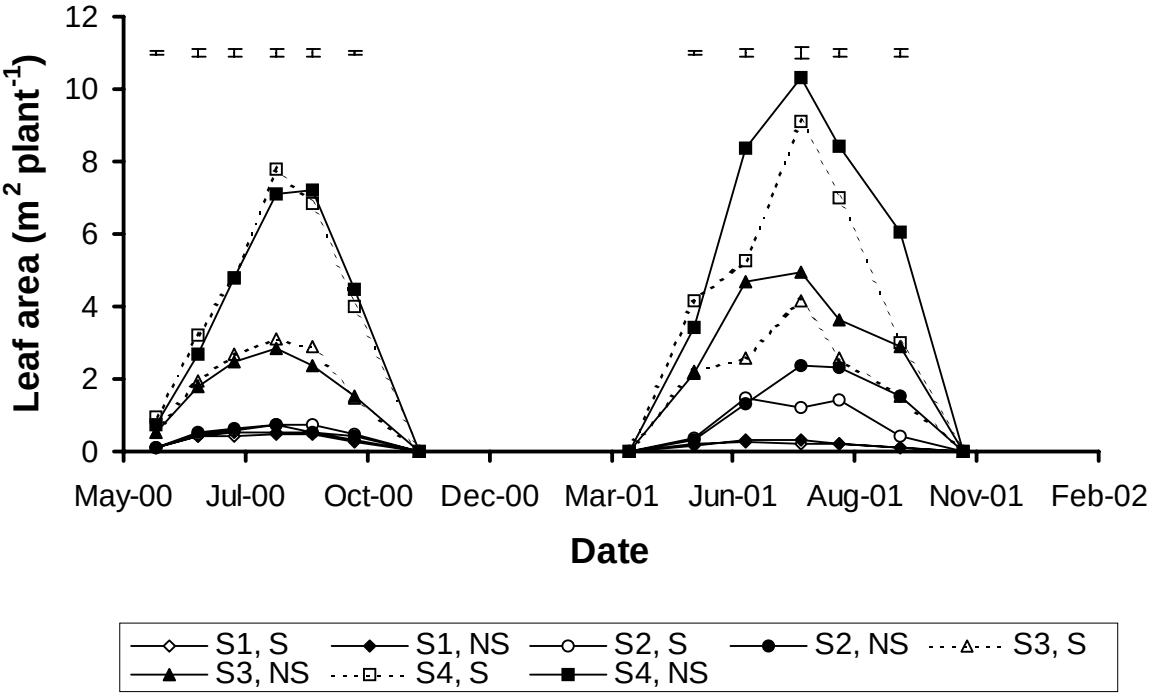

Figure 2. Plant leaf area of soil and water stress treatments during 2000 and 2001. Bars indicate the standard error of the difference (14 df) between treatment means at each measurement date. Abbreviations for soil (S1 to S4) and water stress (NS and S) treatments used in the legend are defined in Table 1 and section 2.2.

Stem dry mass production was markedly affected by treatments over the duration of the experiment (Figure 3) with the main effect of soil treatments being significant from June 1999 and water stress from August 2000 onwards. There was also a significant soil x stress interaction from September 2000 resulting from the proportionately smaller effects of stress on plants in the S1 and S3 treatments compared with those in the S2 and S4 treatments. Amongst the non-stress treatments at the end of 2001, stem dry mass was almost ten times greater (2.53 kg plant^{-1}) in the amended (S3) than in the unamended clay (S1; 0.28 kg plant^{-1}) but this was still only 41% of that produced on the sandy loam soil (S4; 6.23 kg plant^{-1}). Compared with the non-stress treatments, stress reduced stem dry mass by between 26% and 36% at the end of the experiment. In the first two years, reducing soil bulk density alone (S2) resulted in only a small increase in stem dry mass compared with the high bulk density treatment (S1). In the third year, following the application of fertiliser to the S2 treatment, there were much larger, significant differences between these treatments.

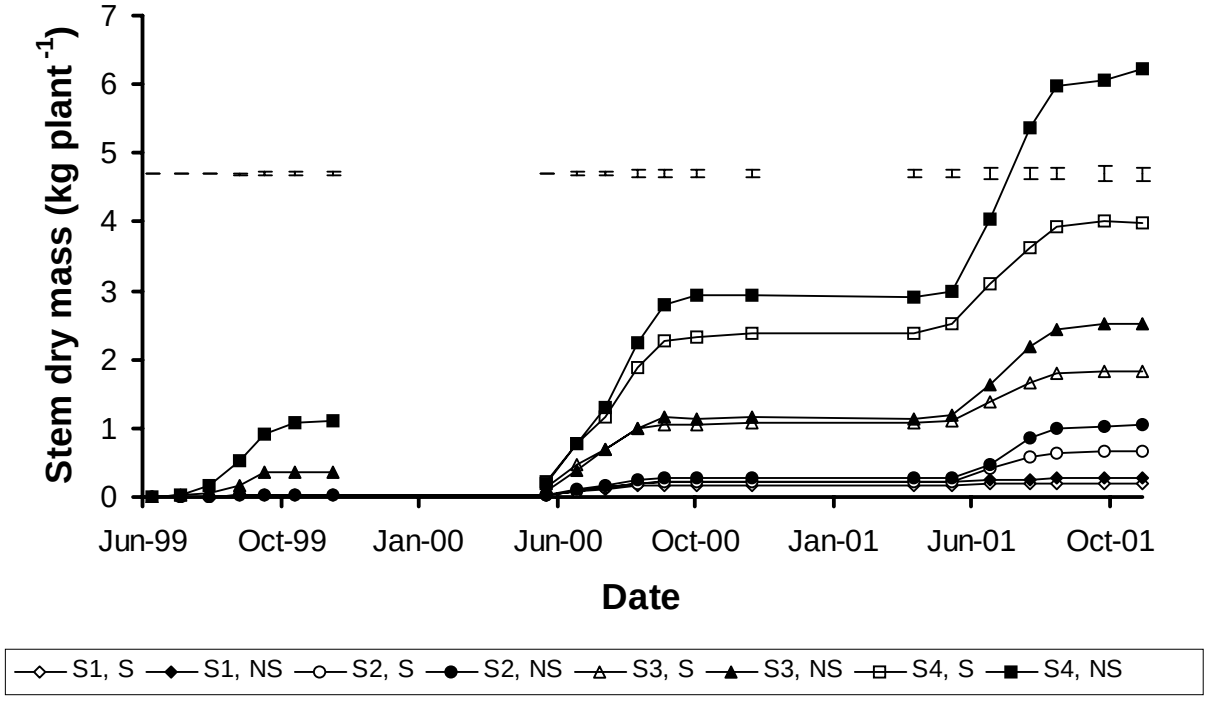

Figure 3. Estimated stem dry mass plant-1 of soil and water stress treatments from 1999 to 2001. Bars indicate the standard error of the difference (18 df in 1999 and 14 df in 2000 and 2001) between treatment means at each measurement date. Abbreviations for soil (S1 to S4) and water stress (NS and S) treatments used in the legend are defined in Table 1 and section 2.2.

In both 2000 and 2001, there were significant linear relationships between stem dry matter production over the growing season and LAD. There were, however, significant differences between the relationships for stressed and unstressed plants with the slope of the line for stressed plants being less than that for unstressed plants. This can largely be attributed to differences in dry matter partitioning. **Figure** 4 shows these relationships for plants in 2001.

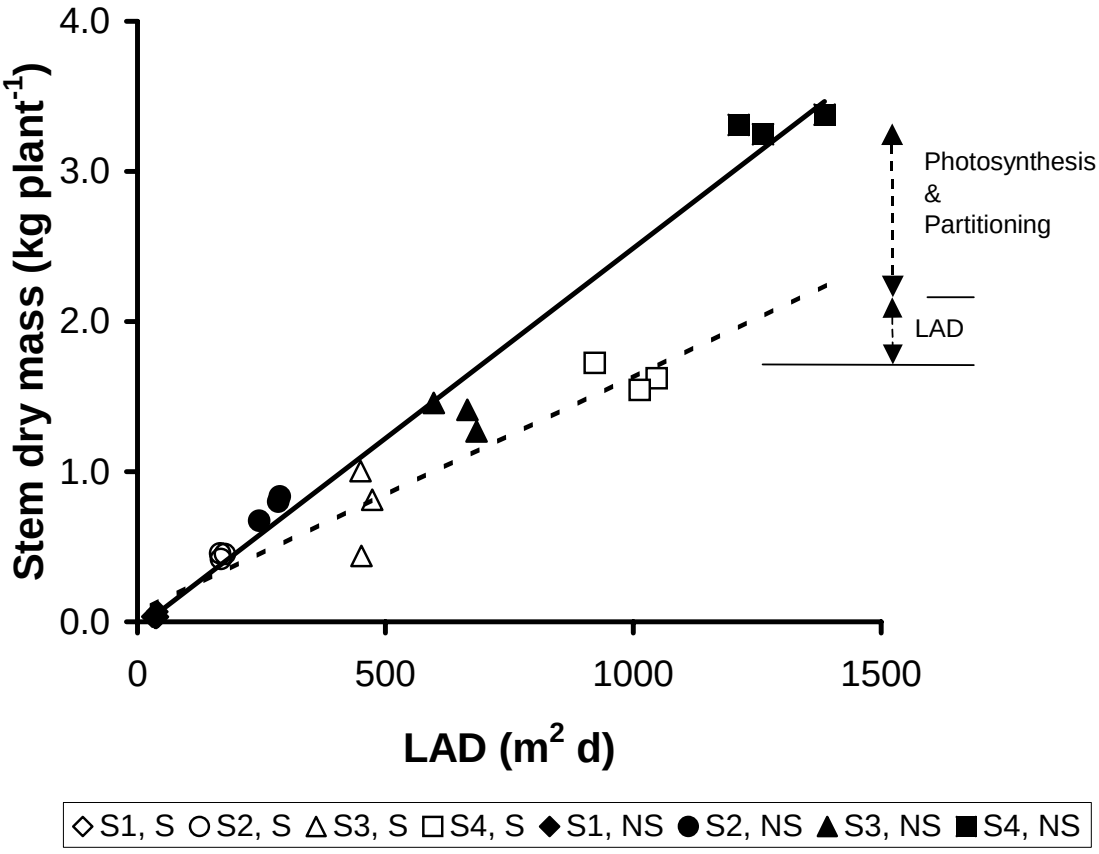

Figure 4. The relationship between stem dry matter accumulated in the 2001 growing season and LAD for non-stressed (solid line) and stressed plants (dashed line). The equation of the line for non-stressed plants is y = 2.53x – 44.89 (se of the slope, 0.12; se of the intercept, 86.6; r^2, 0.98). The line for stressed plants is y = 1.58x + 60.52 (se of the slope, 0.13; se of the intercept, 11.7; r^2, 0.93). Double-headed arrows indicate the reduction in stem dry weight of the S4 stressed treatment attributable to i) reduced LAD and ii) partitioning and reduced net photosynthesis. Abbreviations for soil (S1 to S4) and water stress (NS and S) treatments used in the legend are defined in Table 1 and section 2.2.

3.3 Root growth

When harvested in November 2001, there were large differences in root biomass between the treatments (Table 4), although these were not always the same as those seen for stem dry mass. Thus, total root dry mass was significantly affected by soil type and amendment but not by water stress. Stress resulted in a different distribution of roots down the soil profile so that unstressed plants had significantly more root in the top 0.2 m while stressed plants had significantly more from 0.4 - 0.6 m and below 0.6 m. In addition, plants in the clay soil treatments had a higher proportion of their root dry mass in the top 0.2 m than those in the sandy loam (71% compared with 43% for unstressed plants and 50% compared with 34% for stressed plants) showing that their root systems were generally shallower. In the clay treatments, there was very little development of thick structural roots in the interior of the soil core and most grew outwards to the perimeter of the lysimeter and then down the edge of the soil core. In the sandy loam, structural roots were well distributed throughout the soil core.

Table 4. The effect of soil and water stress treatments on total root dry mass (kg plant-1) and its distribution at different depths. The top part of the table shows treatment means and the bottom part shows the significance of treatment main effects and interactions.

Treatment	Total	0-20 cm	20-40 cm	40-60 cm	>60 cm
S1, NS	0.25	0.20	0.03	0.01	0.01
S1, S	0.30	0.16	0.09	0.04	0.01
S2, NS	1.07	0.74	0.27	0.03	0.04
S2, S	1.25	0.68	0.28	0.14	0.15
S3, NS	2.82	1.77	0.85	0.10	0.09
S3, S	2.80	1.19	0.77	0.47	0.37
S4, NS	3.74	1.63	1.30	0.52	0.30
S4, S	3.17	1.08	1.14	0.61	0.34
SED[a]	0.43	0.13	0.23	0.08	0.07
Probability levels of F ratios for treatment main effects and interactions					
Soil	<0.001	<0.001	<0.001	<0.001	<0.001
Water stress	0.677	<0.001	0.707	0.003	0.004
Soil x stress	0.621	0.018	0.903	0.057	0.041

[a] Standard error of the difference between treatment means with 14 df.

In all treatments, there was a larger mass of fine than coarse root (Figure **5**) and as a percentage of total root mass this was higher in the clay soils (81%, 75% and 72% respectively for S1, S2 and S3) than in the sandy loam (63%).

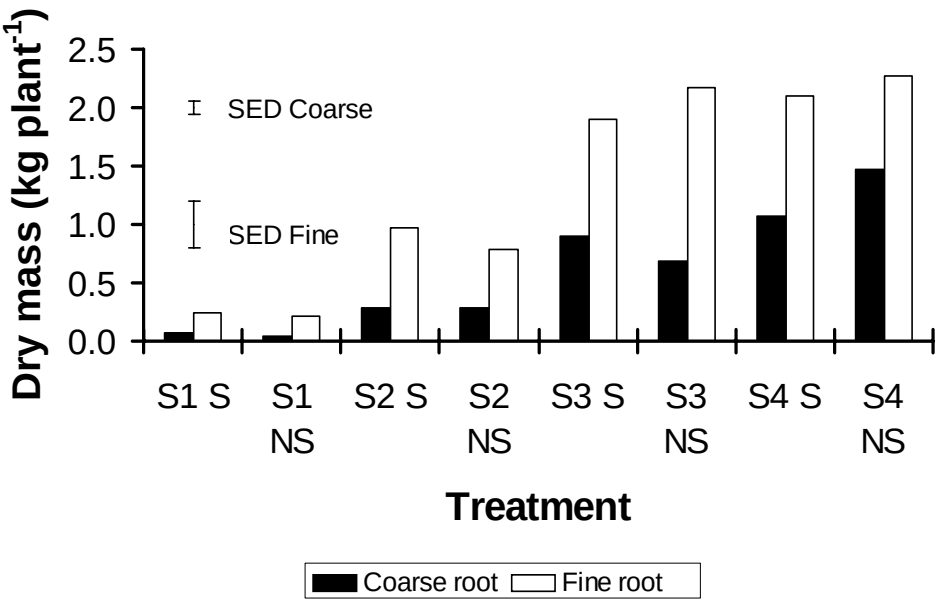

Figure 5. Total dry mass of coarse and fine root plant-1 in the different soil and water stress treatments. Abbreviations for soil (S1 to S4) and water stress (NS and S) treatments used along the x-axis are defined in Table 1 and section 2.2.

3.4 Plant Dry Mass Partitioning

Table 5 shows total plant dry mass in November 2001, the percentage distribution of this in stem, stump and root and plant root:stem ratios for the different treatments. Total plant dry mass was significantly affected by soil, showing the same trends as seen for stem dry mass – i.e. S1<S2<S3<S4. Water stress significantly reduced plant dry mass but there was a significant soil x stress interaction resulting from the proportionately larger reduction of dry mass in stressed plants of the S4 treatment (27%) compared with the other treatments (S3, 14%; S2, 11%; S1, 7%). Soil and stress had significant effects on the proportion of plant mass in root and stem. Thus, plants in the clay (S1, S2 and S3) and water stress treatments had a higher proportion of their dry mass in roots and a smaller proportion in stems compared with those in the sandy loam (S4) and unstressed treatments. Consequently, root: stem ratios were higher in the clay than in the sandy loam and in the stress than unstressed treatments.

Table 5. The effect of soil and water stress treatments on total plant dry mass in November 2001, the percentage of this in stem, stump and root and the root:stem ratio. The top part of the table shows treatment means and the bottom part shows the significance of treatment main effects and interactions.

Treatment	Total plant (kg)	Stem (%)	Stump (%)	Root (%)	Root:stem ratio
S1, NS	0.59	47.4	10.3	42.2	0.90
S1, S	0.55	36.9	9.0	54.1	1.50
S2, NS	2.28	45.7	7.7	46.6	1.02
S2, S	2.02	33.1	5.7	61.2	1.92
S3, NS	5.73	44.6	6.6	48.8	1.13
S3, S	4.91	37.7	6.0	56.3	1.61
S4, NS	10.74	58.0	7.2	34.8	0.60
S4, S	7.82	51.0	8.5	40.6	0.80
SED[a]	0.44	4.8	1.0	5.5	0.65
Probability levels of F ratios for treatment main effects and interactions					
Soil	<0.001	0.002	<0.001	0.004	0.014
Water stress	<0.001	0.002	0.206	0.003	0.003
Soil x stress	0.002	0.802	0.154	0.663	0.464

[a] Standard error of the difference between treatment means with 14 df.

3.5 Plant Nutrition

Soil and foliar samples were analysed for N, P and K in both 2000 and 2001 (Table **6**). Results from 2000 show that levels of N and P were very low in the unamended soils (S1 and S2) and that there were correspondingly low levels of these macronutrients in leaves which were close to, or below, the levels considered deficient in other broad-leaved trees (Taylor, 1991). In the amended clay (S3), levels of N and P were considerably higher than in S1 and S2 but not as high as those in the sandy loam. In 2001, in spite of the fertiliser application to treatments S2, S3 and S4, the foliar content of N was near deficiency by August in all unstressed treatments but considerably higher in the stressed. P showed a similar trend, except that levels were above the deficiency threshold in the S4 unstressed plants. The soil analyses in November 2001 showed that N and P continued to be very much higher in the S4 than S3

treatment and that, notwithstanding the fertiliser application, they were still very low in the S2 treatment.

Table 6. Results of soil and foliar analyses from soil and water stress treatments. Foliar samples were collected in August 2000 and 2001 and soil samples in August 2000 and November 2001.

Year	Treatment	Soil [a]			Leaf		
		Total N (mg kg^{-1})	Extractable P (mg kg^{-1})	Extractable K (mg kg^{-1})	N (g kg^{-1})	P (g kg^{-1})	K (g kg^{-1})
2000	S1, NS	630 (vl)	1.6 (0)	371 (4)	19.7	0.6	16.2
	S1, S	602 (vl)	1.6 (0)	365 (4)	23.1	0.7	19.2
	S2, NS	588 (vl)	1.6 (0)	329 (4)	20.4	0.7	20.6
	S2, S	588 (vl)	1.2 (0)	341 (4)	23.6	0.8	15.8
	S3, NS	1036 (l)	33.0 (3)	301 (3)	26.6	1.1	11.9
	S3, S	770 (vl)	8.0 (1)	329 (4)	27.4	1.3	12.8
	S4, NS	1792 (l)	104.0 (6)	259 (3)	26.5	1.4	13.7
	S4, S	1764 (l)	109.2 (6)	246 (3)	27.7	1.5	13.7
2001	S1, NS	360 (vl)	0.4 (0)	422 (4)	18.6	1.7	17.5
	S1, S	560 (vl)	0.0 (0)	375 (4)	17.6	1.7	16.3
	S2, NS	580 (vl)	2.1 (0)	406 (4)	19.7	1.7	20.5
	S2, S	550 (vl)	0.0 (0)	385 (4)	29.6	2.4	18.8
	S3, NS	1550 (l)	45.2 (4)	342 (4)	20.9	2.0	13.6
	S3, S	1380 (l)	29.4 (3)	259 (3)	27.8	3.2	14.0
	S4, NS	2410 (m)	96.4 (6)	133 (2)	19.8	3.1	21.5
	S4, S	2120 (m)	89.1 (6)	129 (2)	31.7	4.4	15.9
Deficiency levels for leaf samples (Taylor, 1991)					<20-25	<1.4-1.9	<7

[a]Letters in brackets after total N values indicate very low (vl), low (l) and medium (m) levels (Landon, 1984). Numbers in brackets after extractable P and K are MAFF indices which range from a minimum of 0 to a maximum of 9 (MAFF, 2000).

In the fertiliser pot trial investigating willow growth on Oxford clay, significant ($P<0.001$) effects of N and P on stem and leaf dry mass (Figure **6**) and stem height were found after 3 months of plant growth. All of these parameters were affected by significant ($P<0.001$) interactions between the two fertilisers such that the addition of one without the other resulted in only a small improvement in growth while the application of both had a much larger effect. Nitrogen significantly ($P<0.001$) affected the proportion of shoot dry mass in leaf which was 45% for the N treatments and only 31% for those without N.

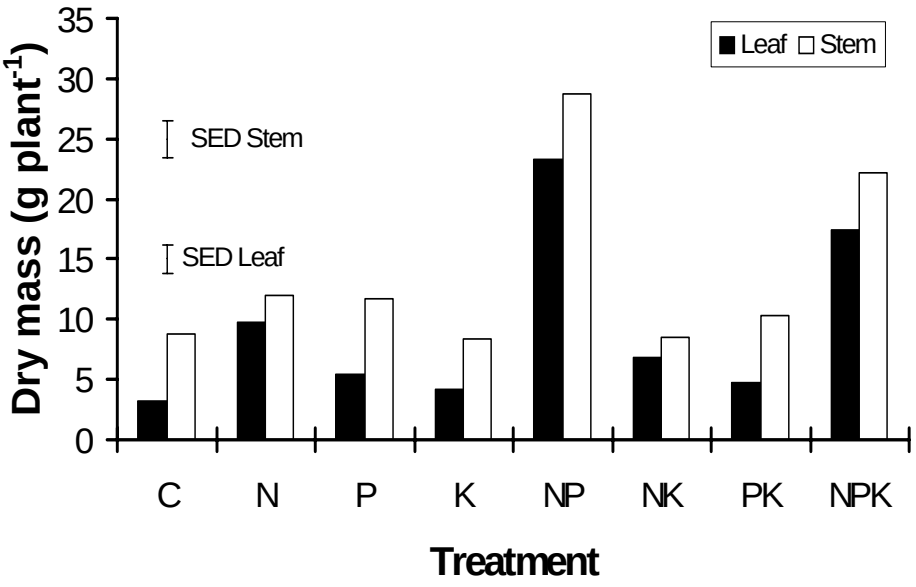

Figure 6. Average dry mass of leaf and stem components of 3-month old plants growing in Oxford clay which received different fertiliser treatments (C, no fertiliser; N, nitrogen; P, phosphorus; K, potassium). Bars represent the standard error of the difference between treatment means (21 df).

4 Discussion

The soil and leaf analyses and pot trial showed that Oxford clay is deficient in N and P. This is also supported by the considerable improvement in growth of S2 plants in 2001 following the application of N, P and K fertilisers. Soil nutritional deficiencies therefore seem to have been the principal cause of the poor growth of S1 plants throughout the trial and can be expected to be a major constraint under field conditions. The low levels of N and P found in the leaves of unstressed S2, S3 and S4 plants in August 2001 suggest that readily available supplies of these nutrients had been exhausted by August. This could have resulted from a combination of uptake (during the vigorous growth of June and July) and leaching and mineralisation. These factors would all have had a larger effect on unstressed than stressed plants, explaining the differences seen between them in foliar N and P levels. Little retention of N and P applied as mineral fertiliser to the clay soil is also indicated by the low levels of these minerals found in the soil of the S2 treatment in November 2001. In this treatment, no additional organic matter had been applied and the low organic matter content of the soil may have predisposed it to leaching. The higher soil N and P in the S3 and S4 treatments would probably have resulted from the Biogran which had still not completely broken down.

In view of the very high correlation between stem dry matter production and LAD (Figure **4**), it is likely that the large effect of nutritional amendment on biomass production can be attributed, principally, to an effect on leaf area development. Differences in plant leaf area between the treatments (S1<S2<S3<S4) were, in part, the result of differences in leaf number per plant - a direct effect of differences in the number of stems and the length of stems, both of which showed the same trend as plant leaf area - S1<S2<S3<S4. There were also treatment differences, however, in the average area leaf^{-1}. Differences between treatments in leaf number and average area leaf^{-1} are demonstrated by data from detailed studies during 2001 on that year's extension growth on the main shoots of plants. These data will be published elsewhere and showed significant differences between soil treatments in the number of leaves shoot^{-1} (26.8 for S1, 33.3 for S3 and 43.5 for S4) and the average area leaf^{-1} (5.9 cm^2

for S1, 7.2 cm^2 for S2 and 11.4 cm^2 for S4). The study also showed that although there were fewer leaves $shoot^{-1}$ and smaller average areas $leaf^{-1}$ in the stress treatment, only number of leaves $shoot^{-1}$ was significantly reduced by stress.

Although small improvements in growth occurred as a result of reducing soil bulk density (S2 plants showed about a 20% increase in stem dry mass over S1 plants at the end of 2000), substantial improvements in biomass production were only obtained by the addition of fertiliser (S2 in 2001) or fertiliser and organic matter (S3). In addition to organic matter, Biogran is a source of nitrogen and phosphorus and this probably accounted for the improved growth of the S3 treatment in 1999 when no mineral fertiliser was used. Nutrient shortages, particularly of nitrogen, have been reported in other studies of trees planted on restored landfill sites (DETR, 2001) and large yield responses of cereals to mineral fertilisers also occurred on a restored London clay site (Sellers et al., 2001). Although the results indicated that nutrition was more important for willow growth than either soil bulk density or organic matter, successful restoration of landfill sites will require attention being given to all three factors. High soil bulk densities can be avoided by appropriate soil placement practices like loose tipping (Dobson and Moffat, 1993b) while organic matter is best incorporated in the cap when it is established.

While soil amendment greatly improved tree growth on the Oxford clay, stem dry matter production $plant^{-1}$ was still only 41% that of plants in the sandy loam soil at the end of 2001. It is possible that their growth was limited by poor soil aeration (Kozlowski, 1986) resulting from waterlogging. This would have been particularly likely in the unstressed clay treatments where frequent watering, to avoid water stress, resulted in high soil water contents below 0.3 m depth for much of the time. The observation that, in all the clay treatments, the majority of the larger structural roots were confined to the soil surface and soil-lysimeter interface supports this suggestion. Very few of these roots were found in the bulk of the soil below 0.3 m depth. Although biomass production $plant^{-1}$ was not as high in the S3 treatment as in the sandy loam, in field plantings it might be possible to increase production ha^{-1} by using a higher plant density than normal.

The experiment has highlighted the importance of improving the nutritional status of Oxford clay but practical methods of achieving this are restricted by the nature of the crop. Amendment by incorporating Biogran or some other organic matter into the cap is appropriate initially, but it is likely that additional N and P will be required by about the third year of growth. There would be considerable advantage for the landfill industry to develop an appropriate amendment based on composted municipal green waste. Further incorporation of organic fertilisers would not be possible because of the presence of the coppice but top-dressings of sewage sludge or compost could be applied after each harvest of stems. Although considerations of cost and convenience would favour the use of mineral fertilisers, these seem to have been quickly lost from Oxford clay, particularly in the absence of an organic matter amendment. This has also been found in other restoration situations (Bradshaw and Chadwick, 1980) and, for longer cutting cycles, organic amendments provide a more sustained release of nutrients (Adegbidi et al., 2003). Landfill leachate is another potential source of nutrients and its utilisation would be of particular interest to the landfill industry because of the high costs incurred in treating or storing it. Although some studies have found negative effects on survival (Mensar et al., 1983) and plant growth (Wong and Leung, 1989), others have reported improved growth (Ettala, 1988; Cureton et al., 1991). In parallel studies to those in this paper, Brierley et al. (2001) have also found substantial increases in stem biomass production from irrigating willow on Oxford clay with leachate compared with water. In addition to providing nutrients, this would also alleviate water stress resulting from the shallow soil at these sites and their location in low rainfall areas. Although there are

concerns about the long-term sustainability of using leachate because of the build up of salts in the soil (Brierley et al., 2001), trials using SRC for leachate management have been run at some landfill sites (Alker et al, 2002) and practical recommendations made for such systems (WRc, 2002). On Oxford clay soils, however, the protracted period for which these soils are wet, sticky and not trafficable raises additional practical problems affecting the feasibility of mechanised SRC activities at the appropriate time (Martin et al., 2002).

Compared with plants grown on a sandy loam soil, those on Oxford clay allocated a greater proportion of their biomass to roots at the expense of stems. This would be a disadvantage if the sole objective was stem biomass production but not if credits were being earned for soil carbon accumulation or if an objective was the long-term improvement in soil structure by the accumulation of organic matter. A previous study of lysimeter-grown willow (Rytter, 2001) found root:stem ratios (i.e. stem, excluding leaf and stump) of 0.11-0.15 in the second and third year of growth. In the present study, root:stem ratios determined from the same plant parts were very much higher and averaged 1.02 (clay) and 0.60 (sandy loam) in the unstressed plants and 1.68 (clay) and 0.80 (sandy loam) in the stressed plants. Bonneau (2005) investigated the root:stem ratios of 5 hybrid willow clones ("Tora", "Ashton Stott", "Resolution", "Endurance" and LA980289) growing in lysimeters at Silsoe under similar conditions to those of the S4 treatment. These varied from 0.56 to 1.27 in unstressed plants and 0.41 to 0.89 in stressed plants. While the root:stem ratios of the plants in our study fall within the range of those of Bonneau (2005), the root:stem ratios of his stressed plants were consistently lower than the non-stressed. This may be related to the more severe stress regime used in his study. Plant root:stem ratios are affected by a number of factors, including nutrition, and shortages of N and P both result in increases in the root:shoot ratio (Ericsson et al., 1996). Thus, in the energy crop switchgrass (*Panicum virgatum* L.), nitrogen rates of 0, 112 and 224 kg ha^{-1} resulted in root:shoot ratios of 6.1, 2.4 and 1.8 respectively (Ma et al., 2001) while in Norway Spruce (*Picea abies* L. Karst) the application of three different nitrogen levels resulted in root:shoot ratios of about 0.8 (N0), 0.7 (N300) and 0.4 (N600) (George and Seith, 1998). Differences in soil nutrient levels in the present study (Table **6**) may therefore have contributed to the marked differences in root:stem ratio between the clay and sandy loam treatments and may also explain the higher root:stem ratios in unstressed plants compared with Rytter's (2001) fertigated plants which received a daily supply of nutrients. Both studies have shown more biomass in fine than coarse root.

As found in many other studies (Ericsson et al., 1996; Kozlowski, 1982), water stress caused a proportionately larger reduction in stem than root dry mass. Differences in dry matter partitioning also contributed to the different relationship between stem dry matter and LAD in Figure **4**. The reduction in stem dry mass of stressed S4 plants can be divided into two components which can be attributed to: i) the effects of partitioning and, probably, reduced net photosynthesis; and ii) reduced LAD. These components contributed approximately 73% and 27% respectively, to the reduction in stem dry mass in this treatment. It is not possible to separate the contribution of partitioning and reduced photosynthesis since the root biomass was only determined at the end of the experiment. The effects of water stress on water use and the water use efficiency (WUE) of willow SRC are reported in the subsequent paper in this series (Martin and Stephens, 2005).

In conclusion, the present research has indicated that nutritional amendment of Oxford clay landfill cap soil will be fundamental to obtaining reasonable biomass production from willow SRC on such sites. Even allowing for the heavy fertilisation of the sandy loam treatment in the present experiment, the results suggest that production is unlikely to approach that on good agricultural soils. It may be possible to rectify nutritional deficiencies of Oxford clay by using end-products of the landfill industry like composted municipal green waste or landfill

leachate. Irrigation with the latter, as part of a leachate management system, would reduce the effects of water stress on biomass production during dry periods and lower the volume of leachate needing to be stored or treated. Biomass partitioning in willow was shown to be affected by both soil and water stress treatments, emphasising the need for both above- and below-ground monitoring of biomass production to obtain an accurate estimate of total plant production. A larger proportion of plant biomass was allocated to roots on Oxford clay than on a good agricultural soil, suggesting that willow could be used as part of a long-term restoration strategy to increase soil organic matter at these sites.

Acknowledgements

This project was financed by the ***shanks first fund***. The authors are grateful to David Nixon for early work on the experiment and to Gabriela Lovelace and Mary Cook for performing the leaf and soil analyses.

References

Adegbidi, H.G., Briggs, R.D., Volk, T.A., White, E.H., Abrahamson, L.P., 2001. Effect of organic amendments and slow-release nitrogen fertilizer on willow biomass production and soil chemical characteristics. Biomass Bioenergy 25, 389-398.

Alker, G.R., Godley, A.R., Hallett, J.E., 2002. Landfill leachate management using short rotation coppice. Final technical report. WRc Report number CO5126.

Batchelder, M., Mather, J.D., Joseph, J.B., 1998. The stability of the Oxford clay as a mineral layer for landfill. Water Environ Manage 12, 92-97.

Bending, N.A.D., Moffat, A.J., 1997a. Discussion. In: Tree Establishment On Landfill Sites. Research And Updated Guidance. Department of the Environment, Transport and the Regions. Forestry Commission, Edinburgh, (Chapter 3).

Bending, N.A.D., Moffat, A.J., 1997b. The use of thermally dried sludge as an organic amendment to coal minespoils: experience in the establishment of amenity and forest trees on reclamation sites in south Wales, UK. Paper presented at the 2nd European Biosolids and Organic Residuals Conference, Wakefield, 17-19th November 1997.

Bending, N.A.D., McRae, S.G., Moffat, A.J., 1999. Soil forming materials. In: Soil-forming Materials: Their Use in Land Reclamation. Department of the Environment, Transport and the Regions. The Stationary Office, London, pp. 39-46.

Bonneau, L., 2005. Water use efficiency of SRC willow varieties. Unpublished PhD thesis.

Bradshaw, A.D., Chadwick, M.J., 1980. Derelict land problems. In: The Restoration Of Land. Blackwell Scientific Publications, Oxford, pp. 59-72.

Brierley, E.D.R., McDevitt, J.E.M., Thorn, P., Tyrrel, S.F., Stephens, W., 2001. Application of landfill leachate to willow short rotation coppice. Aspects of Applied Biology 65, 321-328.

Cannell, M.G.R., Milne, R., Sheppard, L.J., Unsworth, M.H., 1987. Radiation interception and productivity of willow. J. Appl. Ecol. 24, 261-278.

Cureton, P.M., Groenvelt, P.H. McBride, R.A., 1991. Landfill leachate recirculation – effects on vegetation vigour and clay surface cover infiltration. J. Environ. Qual. 20, 17-24.

Department of the Environment, Transport and the Regions. 2001. Nutrition. In: Woodland Establishment On Landfill Sites – Site Monitoring, pp. 4-9. http://www.planning.detr.gov.uk/welssm/02.htm. Accessed on 28/3/2002.

Dobson, M.C., Moffat, A.J., 1993a. Landfill environment and tree growth. In: The Potential For Woodland Establishment On Landfill Sites. Department of the Environment, HMSO, London, pp. 7-14.

Dobson, M.C., Moffat A.J., 1993b. Recommended practices for successful woodland establishment. In: The Potential For Woodland Establishment On Landfill Sites. Department of the Environment, HMSO, London, pp. 47-58.

Environment Agency, 2004. Landfill. http://www.environment-agency.gov.uk/yourenv/eff/resources_waste_/213982/207743/?lang=_e. Accessed on 20/11/2004.

Ericsson, T., Rytter, L., Vapaavuori, E., 1996. Physiology of carbon allocation in trees. Biomass Bioenergy 11, 115-127.

Ettala, M.O., 1988. Short-rotation tree plantations at sanitary landfills. Waste Manage. Res. 6, 291-302.

George, E., Seith, B., 1998. Long-term effects of a high nitrogen supply to soil on the growth and nutritional status of young Norway spruce trees. Environ. Pollut. 102, 301-306.

Kozlowski, T.T., 1982. Water Supply and Tree Growth. Part I Water Deficits. For. Abstr. 43, 57-95.

Kozlowski, T.T., 1986. Soil aeration and growth of forest trees. Scand. J. Forest Res.1, 113-123.

Landon, J.R., 1984. (Ed), In: Booker Tropical Soil Manual. Longman Scientific and Technical, Harlow, England, p. 138.

Ma, Z., Wood, C.W., Bransby, D.I., 2001. Impact of row spacing, nitrogen rate, and time on carbon partitioning of switchgrass. Biomass and Bioenerg. 20, 413-419.

MAFF, 1986. The analysis of agricultural materials. Reference Book 427. HMSO. London.

MAFF, 2000. Fertiliser recommendations for Agricultural and Horticultural Crops (RB209). The Stationery Office, London.

Martin, P.J., Stephens, W., 2005. Growth of willows in lysimeters on Oxford clay. II Water use. Bioresource Technol.

Martin, P.J., Brierley, E., McDevitt, J., Moffat, A., Stephens, W., Tubby, I., Tyrrel, S., 2002. Biomass production on landfill sites. Final report to **shanks.first**. Institute of Water and Environment, Cranfield University Silsoe.

McElroy, G.H., Dawson, W.M., 1986. Biomass from short-rotation coppice willow on marginal land. Biomass 10, 225-240.

McRae, S.G., 1998. Land reclamation after open-pit mineral extraction in Britain. In: Eds. M.H. Wong, A.M. Wong, Baker, A. (Eds), Remediation And Management Of Degraded Lands. Lewis Publishers, Boca Raton, Florida, pp. 47-62.

Mensar, H.A., Winant, W.M., Bennett, O.L., 1983. Spray irrigation with landfill leachate. BioCycle 24, 22-25.

Moffat, A.J., Houston, T.J., 1991. Tree establishment and growth at Pitsea landfill site, Essex. Waste Management and Research 9, 35-46.

Nixon, D.J., Stephens, W., Tyrrel, S.F., Brierley, E.D.R., 2001. The potential for short rotation energy forestry on restored landfill caps. Bioresource Technol. 77, 237-245.

Rytter, R.M., 2001. Biomass production and allocation, including fine-root turnover, and annual N uptake in lysimeter-grown basket willows. For. Ecol. Manage. 140, 177-192.

Sellers, G., McRae, S.G., Cook, H.F., 2001. The potential for cereal crop production on a former landfill site restored with London clay. Land Contam. & Reclam. 9, 9-19.

Stephens, W., Hess, T.M., Knox, J.W., 2001. The effects of energy crops on hydrology. Aspects of Applied Biology 65, 101-108 .

Taylor, C.M.A., 1991. Forest fertilisation in Britain. Forestry Commission Bulletin 95. HMSO, London.

Wong, M.H., Leung, C.K., 1989. Landfill leachate as irrigation water for tree and vegetable crops. Waste Manage. Res. 7, 311-324.

WRc, 2002. Landfill leachate management using short rotation coppice. Operational guide. WRc Report number CO5127.

Zan, C.S., James, W.F., Girouard, P., Samson, R.A., 2001. Carbon sequestration in perennial bioenergy, annual corn and uncultivated systems in southern Quebec. Agric. Ecosyst. Environ. 86, 135-144.