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Willow growth in response to nutrients and moisture on a clay landfill cap soil. II Water use

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Abstract

This paper describes studies into the effects of soil factors and water stress on water use by willow (*Salix viminalis* L.) on a clay landfill cap soil and a sandy loam. Individual plants were grown in lysimeters containing these soils under different watering regimes and with different soil amendment treatments. Stemflow and throughfall were measured to determine rainfall entering the lysimeters and evapotranspiration (ET) calculated from a water balance. With plentiful water, seasonal ET increased annually in most treatments, reflecting increases in plant leaf area and dry matter production. For the most vigorous plants, in the sandy loam treatment, it increased from about 360 l plant^{-1} in the establishment year to almost 1200 l plant^{-1} in the third year. Seasonal ET was highly correlated with leaf area duration. Nutritional amendment of Oxford clay resulted in plants with larger leaf area and higher dry matter production and seasonal ET than in the unamended treatment. Water stress reduced seasonal ET by up to 41%, as a result of defoliation and stomatal closure. In unstressed plants, in the sandy loam treatment, daily ET rates per unit leaf area reached a maximum of about 1.5 l m^{-2} d^{-1} in July. Without nutritional amendment, water use efficiency (WUE) calculated from plant ET and root, stump and stem dry weight, was low for the unamended Oxford clay treatment (1.4 g kg^{-1}) but was similar in the amended clay (5.0 g kg^{-1}) and sandy loam (4.9 g kg^{-1}) treatments. The study has shown the dependence of biomass production by willow on Oxford clay on both nutritional amendment and water availability. Although both nutrients and water could be supplied at these sites by growing SRC within a leachate management system, there are several practical issues like the narrow window of opportunity for mechanised operations and concerns about long-term sustainability which still need to be addressed.

Keywords: Canopy interception, evapotranspiration, Oxford clay, stemflow, throughfall, water use efficiency, willow

1 Introduction

There are about 28,000 ha of landfill sites in England and Wales (Environment Agency, 2004). Following restoration, they are often under-utilised and one possible post-closure strategy is to grow willow short rotation coppice (SRC) on them to help meet UK Government targets for renewable energy production. Although there could be a number of advantages in this, yields are likely to be limited by several factors including soil characteristics (Nixon et al., 2001). This is particularly the case on Oxford clay sites where soil nutrition and water are important constraints (Martin and Stephens, 2001). At these sites, water availability is limited by compaction, shallow soil, low rainfall and the lack of soil organic matter. As a result, willow will frequently be exposed to water stress resulting in a substantial reduction in growth and biomass production (Martin and Stephens, 2005).

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Water stress results in stomatal closure which reduces both water use and photosynthesis. Water use efficiency (WUE), the dry matter production per unit of water used, is a useful measure that incorporates both these effects. Depending on the purpose of the investigation and data available, the type of dry matter production measured to calculate WUE may vary and total, above-ground or economically important biomass have all been used while ET is often substituted for transpiration. Calculating WUE from transpiration and above ground biomass production (stem plus leaf), Lindroth et al. (1994) obtained values for the same stand of willow of 4.1 and 5.5 g kg^{-1} in two different years. They attributed the annual variation to differences in root:shoot partitioning. Based on these results and those of Lindroth and Cienciala (1996), Lindroth and Bäth (1999) derived a WUE of 6.3 g kg^{-1}, based on total biomass production and transpiration, and used this within a simple yield model to estimate regional SRC production in Sweden. In willow, annual (Lindroth et al., 1994) and clonal (Weih, 2001) variations in WUE have been demonstrated but it is not known how this is affected by soil factors.

Transpiration rates measured for willow and poplar SRC (Hall et al., 1998) are higher than for any other agricultural or tree crop grown in the UK and because of its high potential demand for water, there is considerable interest in the use of willow for treating high-volume liquid wastes (Aronsson and Bergstrom, 2001; Elowson, 1999; Ettala, 1988). On landfill sites, SRC could be used within a system for the remediation of landfill leachate (Brierley et al., 2001; WRc, 2002). This will require an understanding of the factors affecting plant water use at these sites and the identification of those factors promoting a high seasonal water use so that large volumes of leachate can be treated.

The objectives of this study were to quantify water use of willow growing on Oxford clay, to see how this was affected by soil amendment treatments and moisture stress and to compare this with plants growing on better agricultural soils. Since weighing lysimeters were not used and it was not possible to prevent rain from entering them, calculation of a lysimeter water balance required the quantification of stemflow and throughfall. This is also described in this paper.

2 Methods

Details of the experiment were given in Martin and Stephens (2005). A summary is presented below, together with additional information specific to this paper.

2.1 Site, lysimeters and treatments

Individual willow plants (*Salix viminalis* "Jorr") were grown from cuttings between April 1999 and November 2001 in lysimeters, 0.54 m in diameter and 0.9 m deep, at Cranfield University Silsoe, Bedfordshire, UK (52°N, 0.3°W, at 60 m altitude). Plants were cut back in November 1999 and destructively harvested in November 2001.

The experiment investigated three clay soil treatments, selected to simulate different landfill cap conditions: i) compacted cap soil (1480 kg m^{-3}; S1); ii) cap soil cultivated to reduce its bulk density (1270 kg m^{-3}; S2) and iii) cultivated cap soil (1200 kg m^{-3}) improved by the addition of organic matter and fertiliser (S3). For comparison with better growing conditions, a sandy loam soil (Cottenham series) treatment (S4) was included using the same amendments and bulk densities as S3. Biogran (Swiss Combi Technology) was used as a source of organic matter and was mixed into the top 0.1 to 0.4 m of soil of the S3 and S4 treatments at a rate equivalent to 200 t ha^{-1}. 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). In 1999 and 2000, single applications of nitrogen were made to treatments S3 and S4 at a rate of 200 kg N ha^{-1}. In 2001, N, P and K fertilisers at 300, 150 and 90 kg ha^{-1}, respectively, were applied to treatments S2, S3 and S4. The four soil treatments were represented by two lysimeters in each of the three replicates.

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. All lysimeters were well-watered during 1999, the establishment year. Starting from 2000, one plant per replicate in each soil treatment was grown without moisture stress while the other was subjected to cycles of stress. In the unstressed treatment, threshold soil water contents corresponding to a soil water potential of -0.05 MPa at 0.2 m depth were used for watering. These were identified from soil water release curves as corresponding to a volumetric soil water content (θ_v) of 47% for the clay and 27% for the sandy loam. Lysimeters in the unstressed treatment were watered on the days that the soil probes showed these thresholds had been reached. At each watering, measured quantities of water, sufficient to saturate the soil, were added to each lysimeter and excess was then drained off and measured over the following two days. Moisture stress was imposed on the stress treatment by allowing the soil water to drop to wilting point before re-watering. Wilting point was determined visually as the point when the majority of leaves on a plant started to droop. In 2000, plants were watered on the day that wilting occurred while in 2001, watering was on the third day of wilting. The soil probes indicated that wilting occurred at a θ_v, at 0.1 m depth, of about 30% in the clay treatments and 22% in the sandy loam. At the end of the stress period, measured quantities of water, sufficient to return the soil to saturation, were added to each lysimeter, excess was drained off and measured and a new cycle of stress then started. Since rainwater could not be prevented from entering the lysimeters, the imposition of the moisture stress treatment was dependent on the occurrence of rain-free periods. During 2000, 11 cycles of soil drying were imposed on the S3 and S4 treatments and 6 in 2001; fewer cycles were imposed on plants in the S1 and S2 treatments because they used water more slowly and drying cycles were more often interrupted by rain. 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. Since no moisture 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 moisture stress treatment was applied to the same lysimeters in 2001 as in 2000.

2.2 Plant measurements

During the growing seasons, stem diameter was measured monthly to allow the calculation of stem basal area (SBA). Stem dry mass was determined from allometric relationships with SBA (Martin and Stephens, 2005).

During 2000 and 2001, plant leaf area was estimated monthly from relationships between SBA and stem leaf area. In July 2000 and 2001, two measurements were made of maximum plant canopy diameter in a North-South and East-West direction. The average of these was used to calculate the projected ground cover area for each plant, assuming this was a circle. The maximum leaf area index (LAI) for each plant was then calculated by dividing its maximum leaf area by its canopy ground cover area. Plant leaf area duration (LAD) was calculated from 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.

Root dry mass was estimated from soil samples collected from the lysimeters of fine (<2 mm diameter) and coarse root (>2 mm diameter).

2.3 Stemflow, throughfall, canopy interception and ET

During 2001, rain entering the lysimeters was quantified as stemflow and throughfall. Stemflow was measured on 13 stems across the range of stem diameters found on plants (5 to 23 mm in April 2001). Plastic collars were made from funnels of 35 and 70 mm diameter. Holes, slightly larger than the stem diameter, were drilled in the wall of the funnel next to the spout and the funnel wall was then slit from the rim to the new hole. The funnel walls were trimmed down to collars of 10 mm and then fitted around stems at about 0.25 m above their base. They were secured in place with wire clips and all joints sealed with waterproof silicon sealant. Plastic tubing connected the spout to a vented collecting bottle (0.25 to 4.0 l, depending on stem size). In each lysimeter, all the stems on a plant originated from the stump which was located in the centre of the lysimeter. All the stemflow from all the stems on a plant therefore entered the lysimeter and this is what was calculated for inclusion in equation 3 to determine each lysimeter's water balance.

Throughfall was measured under the eight trees in one replicate by placing a single collector on the soil surface of each lysimeter, half-way between the willow stump and the lysimeter wall. Collectors were made from 1.0 l plastic bottles which had a hole drilled in their side into which the spout of a 115 mm diameter funnel was inserted through a rubber bung. The plastic bottle was fixed to the ground with a metal peg so that the rim of the funnel was horizontal. To calculate a lysimeter water balance (equation 3), only the amount of throughfall entering a lysimeter needed to be known and this was calculated as the quantity which fell on an area equivalent to that of the lysimeter's soil surface (0.23 m^2). In the remainder of this paper, this will be referred to as lysimeter throughfall (T_L), to avoid confusion with throughfall received under the entire tree canopy, which will be referred to as total throughfall (T_T).

Stemflow, throughfall and rainfall were recorded over 24 h periods ending at 0900 each day. Rainfall was the average of four measurements from 100 mm rain gauges located between lysimeters within the experimental site. Data were collected for 52 days on which rain occurred between 26th April and 18th October. Relationships determined in 2001 and described below were used to partition rainfall, recorded at the Cranfield University Silsoe meteorological site (0.5 km away from the trial) into stemflow and throughfall in the preceding two seasons. This was possible because appropriate canopy and stem measurements had been made through each growing season, thereby allowing differences in plant size to be dealt with.

ET was calculated for each lysimeter from a simple water balance:

$ET = St + T_L + I - D$ (3)

Where St, T_L and I respectively, are water entering the lysimeter as stemflow (l), throughfall (l) and irrigation (l) and D is water drained from the lysimeter (l). In this case, ET includes soil evaporation but excludes rain intercepted and evaporated from the canopy.

For comparison with ET, reference crop ET (ET_o) was calculated from the Penman-Monteith combination equation (Smith, 1991) using data from the Cranfield University Silsoe meteorological site.

Canopy interception for each plant was calculated as the difference between gross and net precipitation. Net precipitation is the sum of total throughfall (T_T) and stemflow reaching the ground beneath a plant canopy. To calculate T_T, the measurements of throughfall and canopy ground cover area were used to determine the amount of throughfall reaching an area of ground equivalent to the canopy ground cover area of each plant. This was then added to each plant's stemflow. Gross precipitation was calculated as the rain falling on an area of ground equal to each tree's canopy ground cover area.

2.4 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 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.

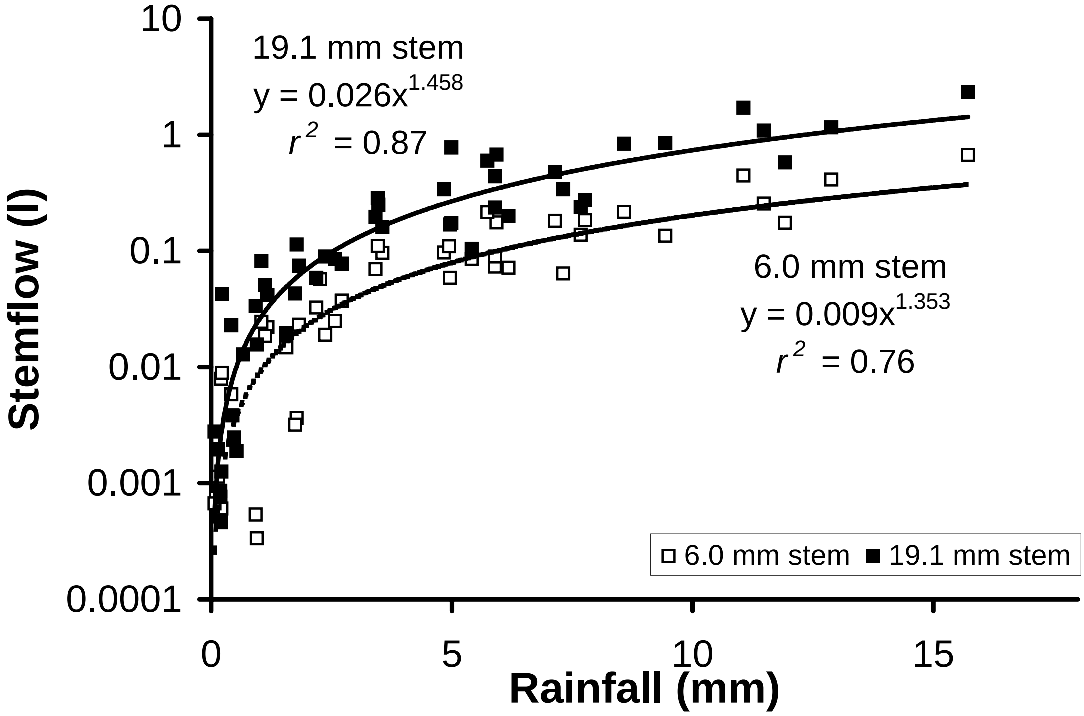

Figure 1 .The relationship between stemflow and rainfall for two willow stems of different diameter.For the 13 stems, stemflow values predicted by calculating values for *a* and *e* from equations 5 and 6 and inserting these in equation 4 accounted for 85% of the variation in actual stemflow values. The same procedure was used to estimate stemflow for all stems on all experimental plants.

3 Results

3.1 Canopy diameter

Measurements of canopy diameter were used to calculate canopy ground cover area. This was then used to determine LAI which was in turn used to derive relationships for calculating lysimeter throughfall (section 3.3) and total throughfall for determining canopy interception (section 3.4). Table 1 shows the variation of canopy diameter in soil and moisture stress treatments in 2000 and 2001. In both years, it was significantly affected by the soil treatments, being greatest in the S4 treatment and decreasing in the other treatments in the order S3>S2>S1. Canopy diameter was not significantly affected by moisture stress, although it tended to be slightly less in most of the stress treatments.

Table **1**. The effect of soil and moisture stress treatments on canopy diameter measured in July 2000 and July 2001. The top part of the table shows treatment means and the bottom part shows the significance of treatment main effects and interactions.

Treatment	Canopy diameter (m), 2000	Canopy diameter (m), 2001
S1, NS	0.85	1.28
S1, S	0.78	1.08
S2, NS	1.04	1.58
S2, S	0.94	1.51
S3, NS	1.39	2.28
S3, S	1.42	2.19
S4, NS	1.58	2.75
S4, S	1.50	2.60
SED[1]	0.08	0.14
Probability levels of F ratios for treatment main effects and interactions		
Soil	<0.001	<0.001
Stress	0.204	0.091
Soil X Stress	0.667	0.905

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

3.2 Stemflow

For the 13 stems, the amount of stemflow collected on each measurement occasion in 2001 was much more highly correlated with rainfall than with any of the measured stem characteristics (SBA, length or leaf area). A power relationship was fitted to the data:

$\mathrm{St} = aX^{e}$ (4)

Where St is stemflow (l), a and e are constants and X is rainfall (mm). The relationship between stemflow and rainfall was described better by a power than a linear relationship and varied significantly between stems. Averaged over all stems, it accounted for 82% of the variation in stemflow over the season (range 76 to 87%). **Figure 1** shows the lines fitted to one of the smallest and largest stems. The lines for the other stems fell between these two.

For each stem, relationships were investigated between the constants a and e in equation 4 and measured stem characteristics. a was found to be most highly correlated with SBA in October ($\mathrm{SBA_{Oct}}$) and e with the natural logarithm of stem leaf area in September ($\mathrm{Ln(LA_{Sep})}$):

$a = 4.206(\mathrm{SBA_{Oct}}) + 2.425$ (5)

(s.e. of the regression coefficient and constant, 0.234 and 0.739, respectively; $r^2 = 0.96$)

$e = 0.078(\mathrm{Ln(LA_{Sep})}) + 0.798$ (6)

(s.e. of the regression coefficient and constant, 0.012 and 0.079, respectively; $r^2 = 0.79$)

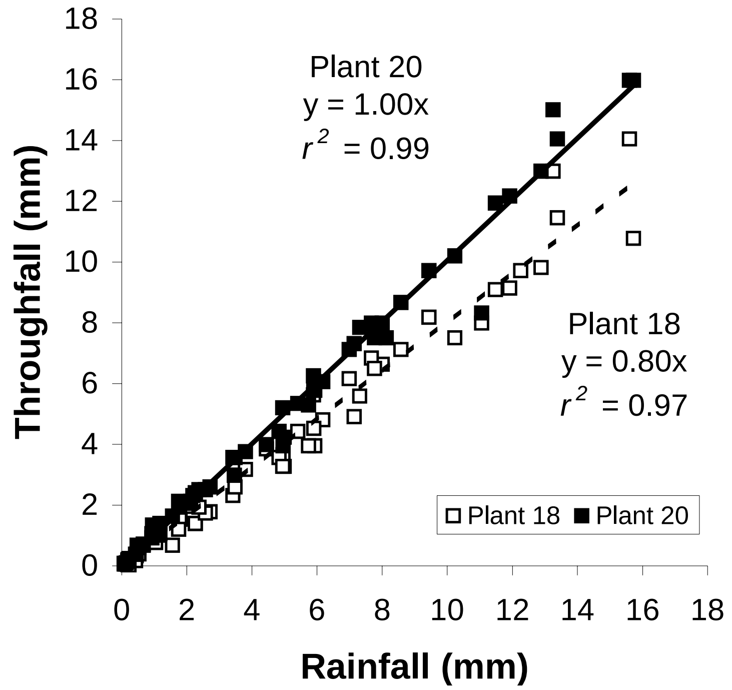

Figure 2. The relationship between throughfall and rainfall for one of the most vigorous (18) and least vigorous (20) plants.

3.3 Throughfall

For all eight plants on which throughfall was measured, there were highly significant linear relationships between throughfall and rainfall but there were significant differences in the relationship between plants. The intercept was not significantly different from zero for any plant and, to facilitate fitting the relationship to plant characteristics, lines were therefore forced through the origin. This made virtually no difference to the coefficients of determination and, averaged over all plants, rainfall accounted for 97% of the observed variation in throughfall. Figure 2 shows the relationship fitted to data for plants with the largest (S4) and smallest (S1) leaf areas. Throughfall for the latter was very similar to rainfall while for the former it was usually less. The fitted lines for the other plants fell between these two.

When the slopes of the lines for the relationships between throughfall and rainfall were investigated in relation to measured canopy characteristics (leaf area, LAI and plant SBA). The greatest amount of variation was accounted for by LAI in July (LAI_{jly}):

$$Y = -0.118X + 1.027 \quad (7)$$

where Y is the slope of the relationship between rainfall and throughfall, and X is LAI_{jly} (s.e. of the regression coefficient and constant, 0.009 and 0.011, respectively; $r^2 = 0.96$).

When slopes for the relationship between throughfall and rainfall were calculated for all eight plants from equation 7 and used to predict throughfall, 97% of the variation in the actual values was accounted for. The same procedure was used to calculate throughfall for the remaining experimental plants.

The amount of throughfall entering a lysimeter (T_L) was calculated as the amount falling on its soil surface. For the 2001 growing season, this was estimated to decrease gradually in the order S1>S2>S3>S4. In contrast, stemflow increased exponentially in the same order so that in S4 plants it was more than ten times greater than in S1 plants (**Figure 3**). The large amounts of stemflow in the S4 and S3 plants resulted from the greater number of large stems in these treatments than in the other treatments. Figure 3 also shows the contribution of irrigation and drainage to the lysimeter water balance of each treatment during 2001.

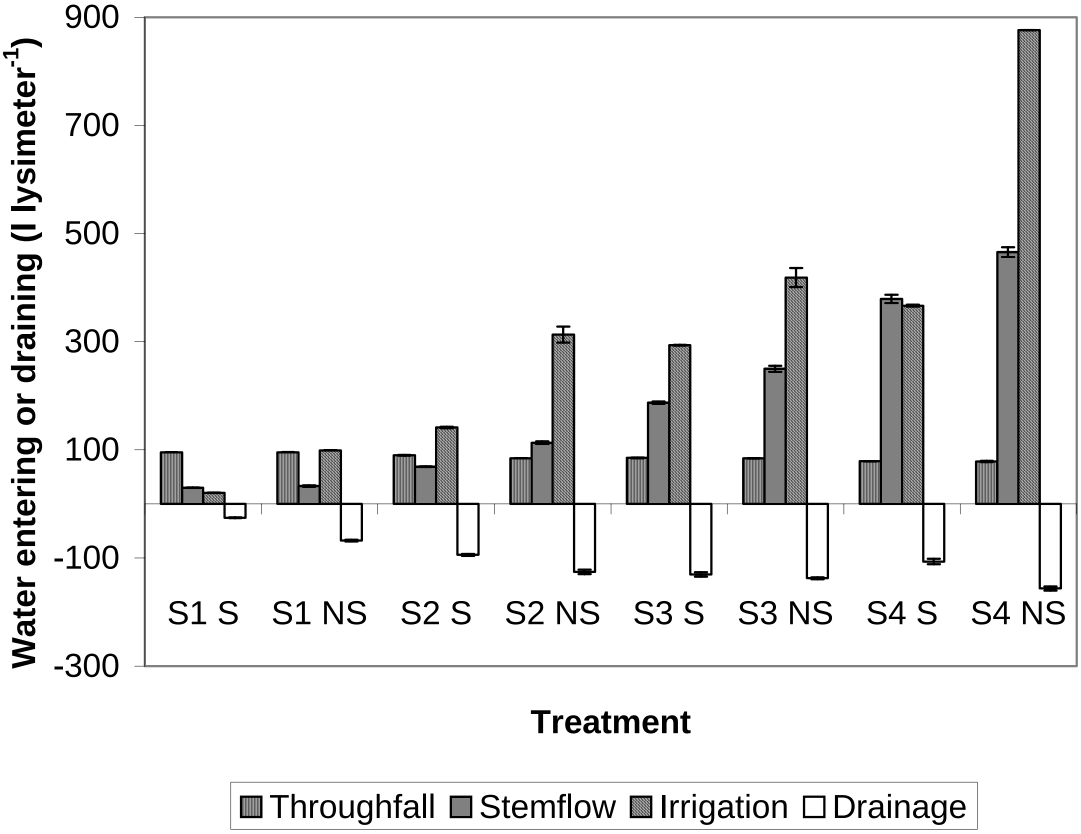

Figure 3. Treatment means for the quantity of water lysimeter^{-1} (l) added as throughfall (T_L), stemflow or irrigation and lost as drainage during the 2001 growing season. Bars indicate the standard error of each mean.

3.4 Canopy interception

As a percentage of gross precipitation over the 2001 season, canopy interception varied from being very little in trees with the lowest LAI to a maximum of about 7% in trees with the highest LAI (Figure 4).

3.5 ET

In all years there were significant differences in annual ET between soil treatments and it decreased in the order S4>S3>S2>S1 (**Error! Reference source not found.**). This order reflects treatment differences in plant leaf area, canopy diameter and stem biomass production. In 2000 and 2001, moisture stress also significantly affected annual ET which was reduced in stressed plants by 10 - 14% in 2000 and 25 - 41% in 2001. The greater reduction during 2001 reflects the use of a more severe stress treatment which resulted in a longer exposure to stress and larger reductions in leaf area because of defoliation. In all treatments, except the S1, there was a progressive increase in annual ET from year to year.

Thus, for the S4 NS treatment, this increased from 359 l plant^{-1} in 1999 to 868 l plant^{-1} in 2000 and 1192 l plant^{-1} in 2001.

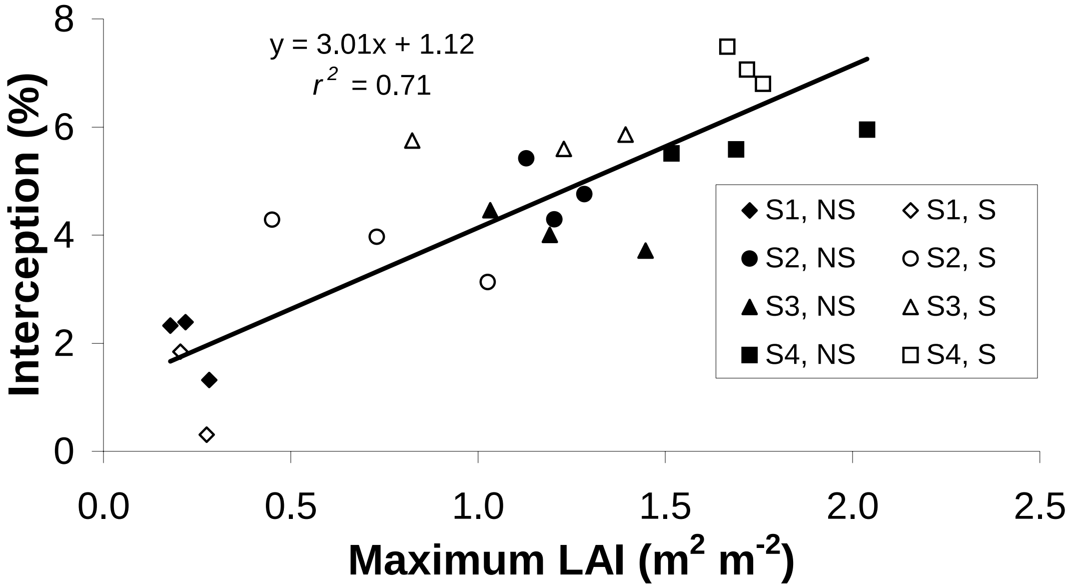

Figure 4. The relationship between plant canopy interception (expressed as a percentage of gross precipitation) and plant maximum LAI during the 2001 growing season

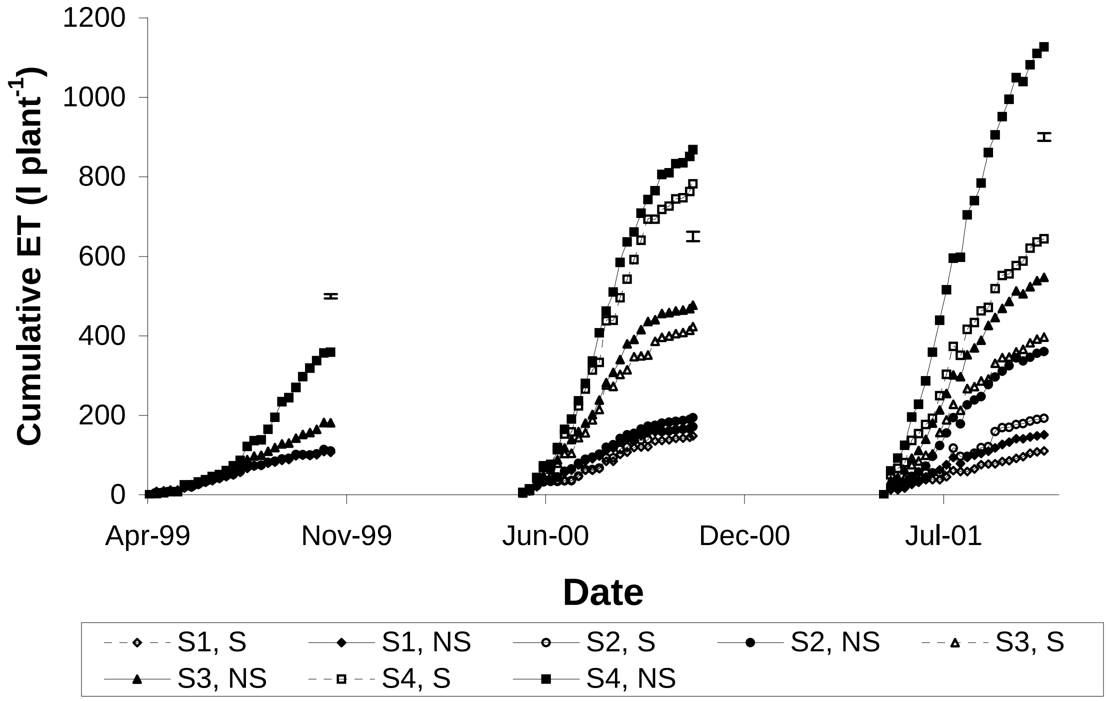

Figure 5. Cumulative seasonal ET by experimental treatments in the three growing seasons. Bars indicate the standard error of the difference between means at the end of each season (18 df in 1999 and 14 df in 2000 and 2001).

Figure 6 shows the seasonal pattern of ET_o and ET for stressed and unstressed plants in the S1, S3 and S4 treatments in 2001. These data were obtained by calculating short-term lysimeter water balances at the end of each irrigation event. Most ET occurred between June and September (67% of seasonal ET for S1 and 78% for the other treatments). In unstressed plants, maximum rates of ET occurred towards the end of July and were 1.4, 5.6, 7.3 and 13.6 l day^{-1} in treatments S1, S2, S3 and S4 respectively. Maximum rates coincided with near maximum leaf areas and slightly after the maximum ET_o values. ET declined rapidly through August and early September and this appeared to be related more to the fall in ET_o than to the decline in leaf area. In 2000, maximum rates of ET occurred slightly later, in August, and were 5.2 and 8.8 l $plant^{-1}$ day^{-1} for unstressed plants in treatments S3 and S4 respectively. In all treatments in 2001, ET was considerably lower in stressed plants from June to August than in unstressed plants.

Linear regression analysis showed that seasonal ET was highly correlated with LAD in both 2000 and 2001. There were, however, significant differences between years and, within years, between the water stress treatments (Figure 7) such that for a given LAD, ET was lower for stressed plants.

Table 2. Treatment means for annual WUE (stem) based on each season's ET and annual stem dry matter production and WUE (plant) based on total ET over 3 growing seasons and plant dry mass in 2001 plus stem dry mass harvested in 1999. The top part of the table shows treatment means and the bottom part shows the significance of treatment main effects and interactions.

Treatment	WUE(stem), 1999 ($g\ kg^{-1}$)	WUE(stem), 2000 ($g\ kg^{-1}$)	WUE(stem), 2001 ($g\ kg^{-1}$)	WUE(plant) ($g\ kg^{-1}$)
S1, NS	0.25	1.34	0.27	1.36
S1, S	------	1.18	0.23	1.56
S2, NS	0.32	1.38	2.01	3.36
S2, S	------	1.25	2.11	4.21
S3, NS	1.98	2.40	2.36	4.95
S3, S	------	2.53	1.74	5.05
S4, NS	3.05	3.37	2.78	4.92
S4, S	------	3.03	2.33	4.82
SED[1]	0.15	0.23	0.20	0.41
Probability levels of F ratios for treatment main effects and interactions				
Soil	<0.001	<0.001	<0.001	<0.001
Stress	------	0.288	0.025	0.226
Soil X Stress	------	0.556	0.080	0.425

[1] Standard error of the difference between treatment means with 18 df in 1999 and 14 in 2000, 2001 and for WUE(plant).

Table 2 presents annual WUE values for the different treatments based on annual stem biomass production (WUE(stem)) and each season's water use and a cumulative WUE (WUE(plant)) which is based on the dry mass of stems, stumps and roots at harvest in 2001 plus stems harvested in 1999 and the total ET over the 3 growing seasons. For WUE(stem), there was a significant effect of soil in all years and WUE(stem) values generally decreased in the order S4>S3>S2>S1. There was a marked increase in the WUE(stem) of S2 plants in 2001 following the application of fertiliser to this treatment but in the other treatments WUE(stem) was highest in 2000, the season after cut-back.

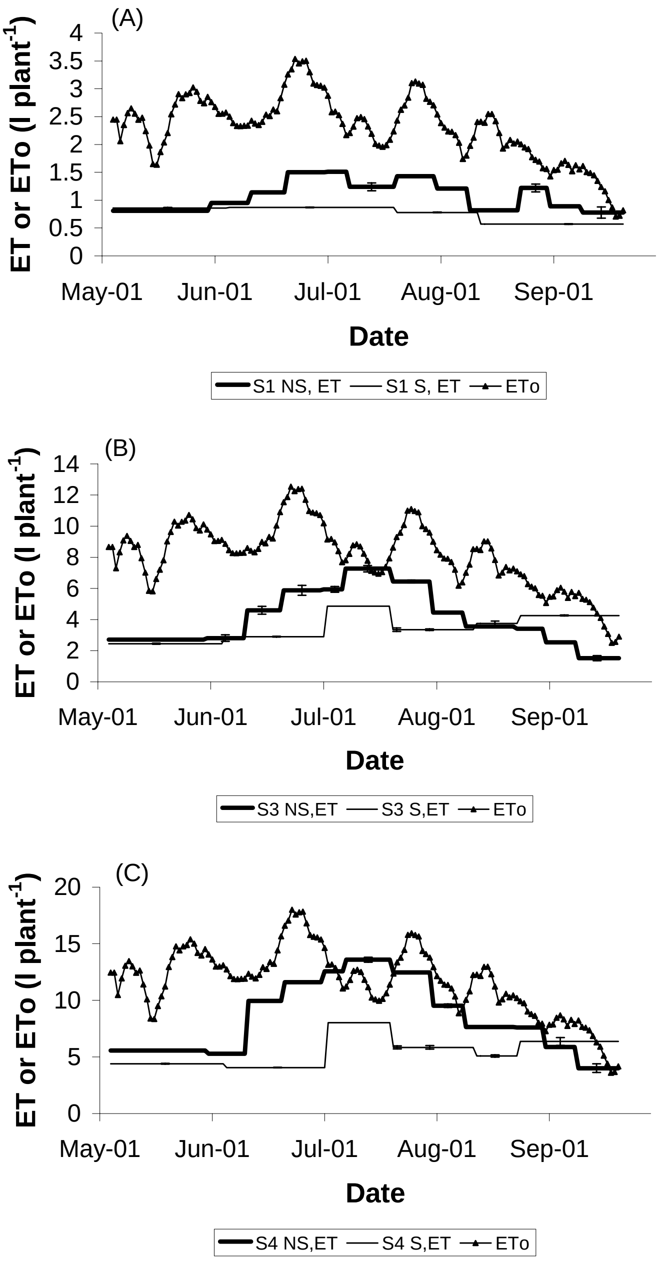

Figure 6. Running 7-day average ET_0 and ET per plant of non stressed (NS) and stressed (S) plants growing in soil treatments S1 (A), S3 (B) and S4 (C) during 2001. ET_0 values in each figure have been calculated for the canopy ground cover area of trees with the average canopy diameter for each treatment. Bars represent the standard error of the means.

Figure 8 shows the individual plant values for total plant dry mass (total plant dry mass in 2001 plus dry mass of stems harvested in 1999) plotted against total water use over the 3 growing seasons. A straight line relationship accounted for 97% of the variation in total biomass and there was no significant difference between the lines for stressed and unstressed plants.

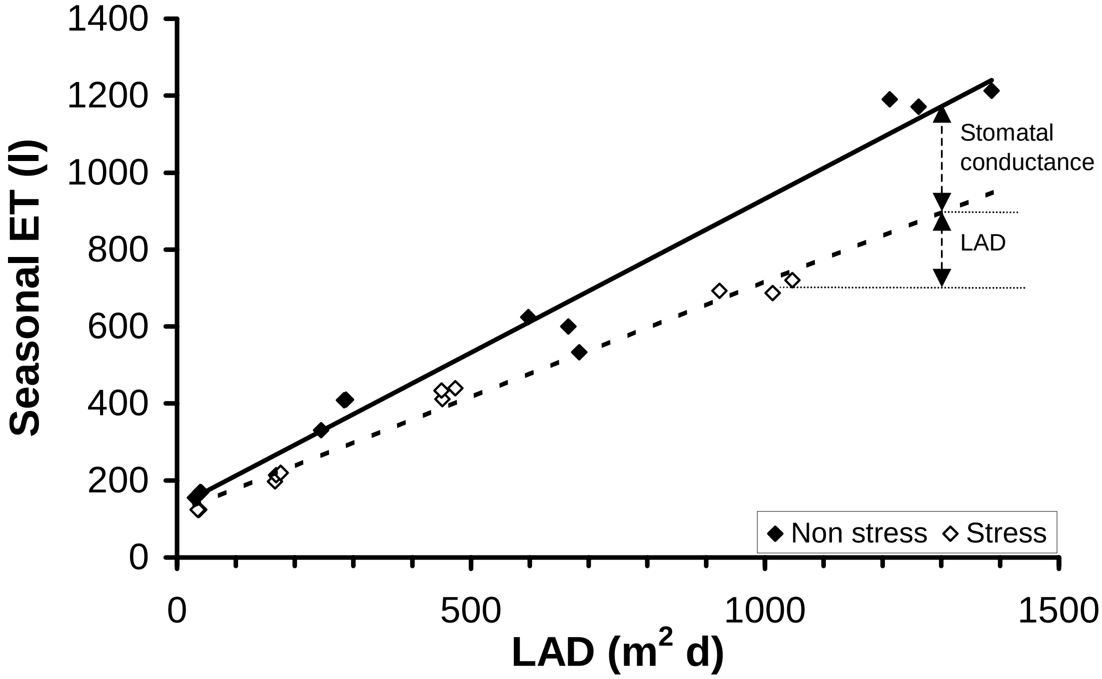

Figure 7. The relationship between seasonal ET and LAD for stressed and non-stressed plants in 2001. The fitted lines are y = 0.80x + 132.78 (se slope 0.04; se intercept 28.31; r^2 0.98; 10 df) for unstressed plants and y = 0.60x + 116.58 (se slope 0.02; se intercept 12.20; r^2 0.98) for stressed plants. The sections indicated by arrows show the reduction in seasonal ET in the S4 treatment attributable to stomatal conductance and to reduced leaf area duration (LAD).

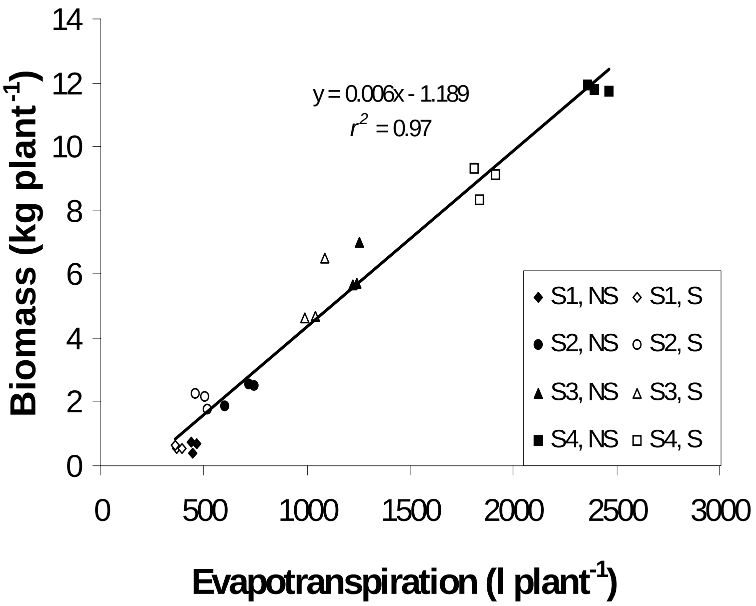

Figure 8. Total biomass plant^{-1} (of stems harvested in 1999 and 2001 and of stump and root harvested in 2001) on cumulative plant evapotranspiration over the same period for different soil and water stress treatments.

4 Discussion

Seasonal ET in willow has been shown to be affected by plant age, soil and water stress. In most of the unstressed soil treatments it increased annually over the first three years. In the second and third season, ET was 2.4 and 3.3 times that of the year of establishment in the unstressed S4 treatments. Within years, seasonal ET was always highest in the sandy loam (S4) treatment, followed by the Oxford clay treatments in the order S3> S2> S1. The important role of leaf area in determining water use is shown by the very significant relationships within watering treatments between seasonal ET and LAD (Figure 7). Previous results demonstrated that the addition of nitrogen and phosphorus fertilisers to willow on Oxford clay resulted in substantial increases in leaf area and growth (Martin and Stephens, 2005). Similar increases have been shown here in ET, the clearest example of this being the much higher rates in plants of the S2 unstressed treatment relative to those in S1 during 2001 after the application of fertiliser (**Error! Reference source not found.**). Nutritional amendment of the S3 treatment, however, did not result in the same vigorous growth and ET as similarly amended plants in the S4, sandy loam treatment. This probably reflects a lack of access to nutrients added to the clay, either because of poor soil aeration or mineralisation and leaching (Martin and Stephens, 2005).

Water stress reduced plant leaf area by causing the premature loss of older leaves and this partly explains the lower LAD and seasonal ET of these plants. In addition, however, the slope of the line fitted to the relationship between ET and LAD (Figure 7) was lower in stressed plants, suggesting lower average transpiration rates per unit leaf area. This was also indicated by the short-term water balance data when expressed on a leaf area basis. Thus, for the unstressed S3 and S4 plants, the ET rates averaged about 1.4 (S4) and 1.5 l m^{-2} d^{-1} (S3) in July while in stressed plants they were about 0.8 (S4) and 1.2 l m^{-2} d^{-1} (S3). This probably resulted from stress-induced stomatal closure (Kozlowski, 1982). In the S4 treatment, about 60% of the reduction in seasonal ET in the stressed treatments could be attributed to stomatal control of water use with the remaining 40% due to a reduction in leaf area (Figure 7). Since the willow plants in this experiment were not part of a continuous dense canopy they were probably well coupled with the atmosphere throughout the season. Control of evapotranspiration would therefore be more dependent on stomatal conductance than on the boundary layer resistance. In willow stands with extensive closed canopies, where ET is closely related to incoming solar radiation, LAD would be expected to be the major factor controlling ET (Perttu and Kowalik, 1989).

In mid-July, when canopy shading would have reduced soil evaporation, the maximum rate of evapotranspiration for the S4 treatment (13.6 l $plant^{-1}$ day^{-1}) was only slightly more than that (13.1 l $plant^{-1}$ day^{-1}) estimated over a similar period (13 July to 3 August) from sapflow measurements (Seymour, 2002 personal communication). At this time, therefore, the peak ET rates for the S4 and S3 treatments can mostly be attributed to transpiration and, on a leaf area basis, are equivalent to about 1.5 l m^{-2} d^{-1} which is towards the upper end of a range of values (0.5 to 1.8 l m^{-2} d^{-1}) given by Kramer and Boyer (1995) for 16 tree species growing in the United States. Willow transpiration has been measured by other researchers using sap flow techniques. In the UK, Hall et al. (1998) found mean daily transpiration rates of about 6 mm d^{-1} for poplar and willow SRC during June and July 1995. The mean flux, about 2.0 l m^{-2} d^{-1}, is larger than the maximum values for S3 and S4 unstressed plants reported here, but might be attributable to the particularly hot and dry conditions of 1995 and to the type of material used for measurements – three-year old stems on four-year old stumps of the clone "Germany" (*Salix burjatica*). For small willow trees in Sweden, Lindroth et al. (1995) calculated maximum daily rates in July and August of 1.2-1.6 l $plant^{-1}$ d^{-1}. The average SBA of these trees was only 7.1 cm^2, however, indicating that they were slightly larger than those in the S1 treatment (6.5 cm^2 in November 2001). Allowing for this, our maximum rates for S1 unstressed plants of about 1.5 l $plant^{-1}$ d^{-1} are similar, but include soil evaporation.

Major differences were seen in WUE(stem) between years and soil treatments. In most treatments, WUE(stem) values were highest in 2000. This may have resulted from the transfer of assimilates from roots after cutting stems back at the end of the 1999 growing season. Exceptions to this were the two S2 treatments which had highest WUE(stem) values in 2001 after receiving fertiliser. The low values of WUE(stem) in all treatments in 1999 probably resulted from soil evaporation being a proportionately larger part of ET in this year. This would be expected because canopy development in the year of establishment is later and less than in the following years and this would have resulted in less shading of the soil and hence greater soil evaporation. This would also explain the very low WUE(stem) of treatment S1 in all years and the higher WUE(stem) of the S2 treatment in 2001 than in the first two years. In spite of the nutritional amendment, the WUE(stem) of the S3 treatment was less than that of the S4 in all three years. This was because proportionately less dry mass was allocated to stems and more to roots in plants in the clay than in the sandy loam (Martin and Stephens, 2005). When WUE(plant) was calculated, there was no difference between the two treatments. Stressed plants also distributed proportionately more dry mass to roots than to shoots so that WUE(stem) was generally lower in stressed than unstressed plants but WUE(plant) was very similar, or even higher, in stressed plants. Differences in dry matter partitioning between the root and shoot also resulted in significant differences in WUE of *Miscanthus* genotypes when calculated on a shoot basis while none existed at the whole plant level (Clifton-Brown and Lewandowski, 2000). These results show the importance, for willow breeders, in considering dry matter partitioning when selecting new clones. Selection for high WUE(stem) or high stem biomass may produce clones which yield well when water is readily available, but these clones may not be suited to dry conditions if stem production is achieved at the expense of root growth.

Under similar conditions to those of the S4 treatment, slightly lower WUE(plant) values (3.56 to 4.71 g kg^{-1}) have been found for 5 hybrid willow clones (“Tora”, “Ashton Stott”, “Resolution”, “Endurance” and LA980289) growing with and without water stress in lysimeters at Silsoe (Bonneau, 2005). The lower values may have been because the hybrid clones were one year younger when they were harvested. Bonneau (2005) found significant clonal differences in WUE(plant) but none as a result of stress.

Under the conditions of the present experiment where tall, spreading, multi-stemmed willow plants in the S3 and S4 treatments were grown in lysimeters with a relatively small projected surface area, stemflow was shown to make a particularly large contribution to the lysimeter water balance. Willow SRC has several characteristics which favour high stemflow rates (Crockford and Richardson, 2000): a high density of near-vertical stems; branches and leaves angled well above the horizontal; and smooth bark. In contrast, lysimeter throughfall (T_L) was much less important, but only because of the small soil surface area of the lysimeters. If, however, stemflow is compared with total throughfall (T_T) – which would be the normal comparison for stand-level studies of SRC - stemflow becomes less important. In this case, it varied from 8% (S1) to 17% (S4) of gross precipitation and T_T from 75% (S4) to 91% (S1) while net precipitation varied from 93% (S4) to 99% (S1) of gross precipitation. These values are larger than generally found for stands of trees. For willow SRC, Ettala (1988) reported stemflow and T_T as 2% and 67%, respectively, of gross precipitation while Hall et al. (1996) estimated the two components to be 79% for a stand of poplar SRC in the UK. It is likely that the difference between these estimates and those in the present study can be attributed to the latter being for individual trees rather than a stand and to the low LAI of these trees which varied from 0.25 (S1) to 1.8 (S4). Similarly high net rainfall (92%) was reported for widely spaced olive trees (*Olea europaea* Linn.) in Spain with a LAI of 1.1 (Gomez et al., 2001) while for Sitka spruce (*Picea sitchensis* (Bong.) Carr) in the UK, Teklehaimanot et al. (1991) found net precipitation depended on tree spacing and increased from 67% to 91% as spacing increased from 2 to 8 m.

In a previous paper (Martin and Stephens, 2005), it was shown that soil nutritional deficiencies and water stress can cause large reductions in biomass production by willow on Oxford clay. Furthermore, the low values for WUE(stem) shown in the present study indicate that, to achieve a given level of biomass production, willow on Oxford clay will also use more water than plants on better soil. These factors are serious constraints if willow is being grown solely for biomass, but not if it is being grown within a leachate management system where biomass is a by-product and a major objective is high water use. In this case, irrigation with leachate would remove the constraint of water stress while the nitrogen and phosphorus in the leachate (DOE, 1995) would remedy the Oxford clay's nutrient deficiencies, promoting a high leaf area and high seasonal ET. Beneficial effects of leachate on the growth of willow on Oxford clay have already been demonstrated (Brierley et al., 2001). Such a system could adopt a number of cultural practices to encourage high water use. For example, using close spacing, selecting planting designs which encourage advection, atmospheric coupling and a high crop coefficient (Stephens et al., 2001), siting the SRC in exposed areas and selecting clones with a high water use. Clones and husbandry could also be managed to achieve a high LAI early in the season in order to maximise radiation interception (Cannell et al., 1987) and take advantage of the high rates of potential ET from June to August. In spite of the advantages of such a system, there are a number of issues to be resolved before such a system can be implemented on Oxford clay (Martin et al., 2002). One major practical constraint is that wet and sticky soil conditions leave only narrow windows of opportunity for performing critical SRC operations such as planting and harvesting. In the long-term, there is also concern about the sustainability of such a system, particularly because of increases in soil salinity over the irrigation period and the loss of salts from the soil over the winter.

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