Available online at www.sciencedirect.com

ScienceDirect

Biomass and Bioenergy 31 (2007) 460–468

BIOMASS & BIOENERGY

www.elsevier.com/locate/biombioe

The effect of water availability on stand-level productivity, transpiration, water use efficiency and radiation use efficiency of field-grown willow clones

Maj-Lena Linderson[a,b,*], Zinaida Iritz[c], Anders Lindroth[a]

[a]*Department of Physical Geography & Ecosystems Analysis, Geobiosphere Science Centre, Lund University, Sölvegatan 12, S-223 62 Lund, Sweden*
[b]*Risø National Laboratory, Bio Systems Department, Technical University of Denmark, Frederiksborgvej 399, 4000 Roskilde, Denmark*
[c]*Swedish International Development Cooperation Agency, S-105 25 Stockholm, Sweden*

Received 16 March 2006; received in revised form 15 January 2007; accepted 15 January 2007
Available online 23 March 2007

Abstract

The effect of water availability on stand-level productivity, transpiration, water use efficiency (WUE) and radiation use efficiency (RUE) is evaluated for different willow clones at stand level. The measurements were made during the growing season 2000 in a 3-year-old plantation in Scania, southernmost Sweden. Six willow clones were included in the study: L78183, SW Rapp, SW Jorunn, SW Jorr, SW Tora and SW Loden. All clones were exposed to two water treatments: rain-fed, non-irrigated treatment and reduced water availability by reduced soil water recharge. Field measurements of stem sap-flow and biometry are up-scaled to stand transpiration and stand dry substance production and used to assess WUE. RUE is estimated from the ratio between the stand dry substance production and the accumulated absorbed photosynthetic active radiation over the growing season. The total stand transpiration rate for the 5 months lies between 100 and 325 mm, which is fairly low compared to the Penman–Monteith transpiration for willow, reaching 400–450 mm for the same period. Mean WUE of all clones and treatments is 5.3 g/kg, which is high compared to earlier studies, while average RUE is 0.31 g/mol, which is slightly low compared to other results. Generally, all clones, except for Jorunn, seem to be better off concerning biomass production, WUE and RUE than the reference clone. Jorr, Jorunn and Loden also seem to be able to cope with the reduced water availability with increase in the water use efficiency. Tora performs significantly better than the other clones concerning both growth and efficiency in light and water use, but the effect of the dry treatment on stem growth shows sensitivity to water availability. The reduced stem growth could be due to a change in allocation patterns.

Keywords: Willow; Field-grown; Productivity; Transpiration; Water use efficiency; Radiation use efficiency; Up-scaling; Southern Sweden

1. Introduction

Short-rotation forests are developed and used in Europe and North America as a dedicated crop for bioenergy. Due to its high production potential, demonstrated by, e.g. Christersson [1], willow became the major energy crop in Sweden [2]. Despite its high potential, the expansion of full-scale willow plantations for energy use ceased in the late 1990s. This was partly caused by lower harvests than expected [3] and water availability was identified as one of the main factors limiting the production [4]. The transpiration from fast growing willow cultivations is high [5–7], which results in a high water demand during the growing season. In the main cultivation areas in southern Sweden, precipitation during the growing season is shown to be lower than the potential evaporation from willow stands growing under non-limiting conditions [4]. Moreover, frequent dry spells may cause significant losses in biomass production. Dry periods during April–May, while the willow growing-rate is the highest, occur almost every year in Scania in southernmost Sweden [8].

Today, Swedish breeders work on the improvement of plant material in order to maximise the willow production

*Corresponding author. Department of Physical Geography & Ecosystems Analysis, Geobiosphere Science Centre, Lund University, Sölvegatan 12, S-223 62 Lund, Sweden. Tel.: +46 46 222 84 07; fax: +46 46 222 03 21.
E-mail address: Maj-Lena.Linderson@nateko.lu.se (M.-L. Linderson).

0961-9534/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.biombioe.2007.01.014

and several new willow clones are commercially available for cultivation. Basic breeding goals include fast growth, straight stems, tolerance to frost and resistance to leaf rust and certain insect pests [9]. Nevertheless, as the use of irrigation is not economically viable in short rotation forests, it is important to take effects of water availability into consideration. Earlier work shows that the biomass production and water use of willow is strongly affected by the selection of clonal material [10]. Concerning the sensitivity to water stress, large variations between willow clones has been identified using pot grown plants [11]. Still, the question of water use and growth limiting conditions on stand level is not fully understood and may thus be further studied to evaluate the suitability of new willow clones for a larger site-range.

To evaluate the differences in the productivity as well as the adaptivity to water limiting conditions on stand level, knowledge about the stand transpiration is needed. Transpiration can be estimated at different scales. Micro-meteorological techniques, like eddy covariance methods, require large homogeneous areas as well as separation between soil evaporation, interception evaporation and plant transpiration [12]. This method is, thus, not suitable for simultaneous measurements at different clones grown in small plots. Shoot level chamber measurements are often used for water flux measurements at single stems. Nevertheless, the internal variation within a willow stand is large due to competition between the shoots and stools [13]. Thus, several simultaneous measurements are required which makes the chamber measurement impractical. A method that has come into focus recent years is sap-flow measurements of single stems [14]. The relatively simple technique enables many simultaneous measurements under similar environmental conditions, which facilitates the up-scaling to stand level as well as the comparisons between different clones. Sap-flow techniques allow long continuous recording of plant transpiration with high time resolution. This enables a better understanding of the processes involved and the effect of, e.g., shorter periods of drought that is not evident from mean values over months or seasons. The estimated water fluxes are shown to agree well with chamber measurements [15].

Standard procedures exist for estimation of productivity of willow short rotation forests [16]. Nevertheless, the growth has to be put into relation to the amount of water used to reveal the water need and the sensitivity to water stress of the different clones. A well-established measure is the water use efficiency (WUE). WUE enables comparisons independent of differences in growth rate and initial size of the different clones. In earlier work on willow, WUE has been successfully used to reveal the influence of climate on carbon allocation [17] and to analyse WUE at different scales [18]. These studies do, however, only include single willow clones and does not separate stem biomass production, which is of interest for energy use.

The aim of this study is to evaluate the effect of water availability on stand-level productivity, transpiration, WUE and radiation use efficiency (RUE) of field-grown willow clones. This is achieved by field measurements of stem sap-flow and biometry measurements for different willow clones and water treatments. These measures are then up-scaled to stand transpiration and stand dry substance production for the different willow clones. WUE is assessed using total stem biomass production and stand transpiration over the growing season. RUE is estimated as the ratio between total stem biomass production and accumulated absorbed photosynthetic active radiation (APAR).

2. Materials and methods

2.1. Experimental design and treatments

Six willow clones were included in the study: L 78183, SW Rapp, SW Jorunn, SW Jorr, SW Tora and SW Loden. L78183 has been selected from field-collected plant material [19] whereas all the others have been bred. All clones except Loden and Tora belong to the species *Salix viminalis*, Loden belongs to the species *Salix dasyclados*/*Salix burjatica* and Tora is a hybrid between *S. viminalis* and *Salix schwerinii*. Jorunn and Jorr are half-sibs.

The plantation was established in spring 1997, in Scania, the southernmost province of Sweden. The plantation is a part of an approximately 4 ha large, commercial plantation of the cultivar Tora on clay soil. Six new willow clones, bred at Weibull AB, were planted in randomised block design. The plantation consisted of four replicates, 48 plants per plot, in three double rows with 0.65 m between plants and row spacing of 1.5 and 0.75 m. The plantation was originally established by Weibull AB as a part of their research on willow.

The plantation was exposed to two water treatments: rain-fed, non-irrigated treatment (RT) and dry treatment (DT) by reduced soil water recharge. The reduction was achieved by coverage of plastic sheeting between the rows on 5 July 2000 (Julian day 187) and until the end of the growing season.

2.2. Data and measurements

All measurements were made during the growing season year 2000. Data sampling covers all stages of canopy development, from leaf emergence until the end of the growing season.

2.2.1. Meteorological measurements

Meteorological data (temperature, humidity, global radiation, photosynthetic active radiation (PAR), wind speed and wind direction) were recorded continuously in an automatic weather station mounted on the top of the 7.5 m high tower mast suited within the stand. All meteorological data were recorded on a data logger (CR-10, Campbell Sci., Logan, USA) every 10 min from 11 May to the 23 October 2000. From 20 June, soil water content was measured every 10 min using a simplified version of time domain reflectometry (TDR) techniques [20]. One soil water content metre for each willow clone and treatment were used. The rainfall measurements origins from the SMHI precipitation network gauge at Svalöv (no 5356).

A supplementary 6.5 m high tower mast was placed on grassland, 15 m from the plantation, and recorded global radiation, PAR, wind speed and direction starting at 26 April. Missing data at the mast inside the plantation were as far as possible substituted by the data from the supplementary mast. The PAR time series start on 26 April. To enable estimation of the cumulated intercepted PAR, daily PAR values from the 19 until 25 April were interpolated from the number of sunshine hours at Copenhagen, using a linear regression equation.

2.2.2. *Stem growth and total stand production*

To cover the large variability of willow stools and stems due to competitive interactions with neighbouring trees [13], stem diameters at 50 cm height of all stems of 12 stools (corresponding to 25% of the stools) for every willow clone and treatment were measured three times from April to October. The resulting diameter frequency distribution for each clone was used to estimate cross-section area frequency distribution, used in the up-scaling of sap flow to stand transpiration rates.

Woody biomass was estimated through a statistically established relationship between stem diameters and dry material weight of the stems [16] based on destructive measurements of stem diameters and dry matter weight in April 2000 (Table 1). An exponential model is often used, with intercept depending on measurement height [16] and exponent varies with stand age [21], factors that are more important that clonal differences [13,21]. As the age and site were the same for all clones and treatments, the same equation could be used for all clones and treatments ($R^2 = 99.3\%$):

$$\mathrm{WB} = 79.6497 - 14.5253\,\mathrm{SD} + 1.59616\,\mathrm{SD}^2, \quad (1)$$

where WB = woody biomass and SD = stem diameter.

Table 1
The parameters and variance explained of the equations used for estimating normalized sap-flow density from cross-section area of the stems for each clone at RT $Q\mathrm{norm} = a\ln(\mathrm{CSA}) + b$ (Eq. (4))

Clone	a	b	R^2
L78183	0.1563	2.1298	0.03
Jorr	0.3935	4.0249	0.53
Jorunn	0.2270	2.6810	0.20
Loden	0.1440	2.1507	0.35 (0.50)
Rapp	0.5381	5.0591	0.81
Tora	0.5223	4.5548	0.79

R^2 shows how much of the variance in Qnorm that can be explained by the model. For each clone, 7–9 sap-flow density measurements were used. For Loden, R^2 within brackets corresponds to one outlier removed.

Total woody biomass per hectare for each willow clone and treatment was estimated from the product of the average woody biomass/stool and the total number of stools per hectare.

2.2.3. *Leaf area index*

Canopy leaf area index (LAI) was measured repeatedly during the growing season in each plot using a Plant Canopy Analyser (LI-Cor 2000, Inc. Lincoln, UM). For the early measurements (before mid-June), only a few measurements of LAI were made. The mean value of these measurements was used as starting LAI values for all clones. Thereafter, LAI was measured for all clones and treatments. To enable estimation of the cumulated intercepted PAR, daily LAI values from 19 April to 3 June was interpolated from the temperature sum at Hörby, using a linear regression equation. From these interpolations, the LAI values for leaves were estimated to be zero before the 20 April for all clones. Bark area was estimated to 0.38, based on measurements before leaf emergence, and was excluded from the LAI time series.

2.2.4. *Sap-flow measurements*

Transpiration rates can be determined by techniques that measure the rate at which sap ascends stems. The theory and practice of these techniques are well described in the literature (e.g. [14,22]) and thus not treated here. Generally, the choice of method depends on application. In this study, a large amount of sap-flow metres were needed and thus, the Granier sap-flow technique was used due to the simplicity and low costs of the method. The design and operation of the Granier sap-flow metres are well described by Granier [23,24] and Lundblad [25]. Here only a brief summary follows.

Two cylindrical probes, one heated and one non-heated, are inserted radially into the stem. The difference in temperature between the two probes is used as a function of sap-flow velocity (g/s): the lower the temperature difference between the probes the higher the sap-flow rates giving the empirical relationship:

$$Q = 119\,K^{1.231}, \quad (2)$$

$$K = \frac{\delta T_0 - \delta T}{\delta T}, \quad (3)$$

where δT corresponds to the temperature difference between the two probes and δT_0 is the temperature difference at zero sap flow. δT_0 is calibrated at low net radiation, high humidity and the presence of intercepted water at leaf surfaces, e.g., at nighttime during rainy days. In order to minimise the temperature gradients along the probe, the heated probes were enclosed into thermally conductive metal tube.

For willow, the stem sap-flow density is correlated to the stem cross-sectional area [15,26]. Thus, the number of probes was selected to represent the range of stem sizes for each clone within the observation plots. This was based on the stem diameters measured in April (Section 2.2.2). Three sizes of probes were used, with a diameter of 2 mm and length of 21, 16 and 11 mm, respectively. Some of the probes could not be used in the analysis due to a large number of missing observations. Sap-flow velocity was measured at a height of 1.5 m.

2.2.5. Estimation of total stand transpiration

The sap-flow density measurements from all probes together with the cross-section area frequency distribution were used to estimate the mean transpiration of each clone and treatment at stand level (mm).

A logarithmic function was fitted for each clone to account for the increase of sap-flow density (Q, kg/m^2 day) with cross-section area (CSA, m^2) of the stems. To eliminate the influence of the weather on the sap-flow values, the sap-flow density series were first normalised by the mean sap-flow density of the clone ($Q\text{norm} = Q/Q_{\text{mean}}$):

$$Q\text{norm} = a\ \ln(\text{CSA}) + b. \tag{4}$$

Clones with thicker stems have smaller coefficients and thus a lower increase with cross-section area (Table 1). This is reasonable as the increase in cross-section area corresponds to an increase in leaf area [15,26] and thus depends on the stem diameter distribution of the clones.

The cross-section area frequency distribution was used to group the stems into cross-section area classes, i, with a class interval of 1 cm^2. This was done for the three occasions when the stem diameters were measured. The class total sap wood area was determined and then used to estimate the class total sap wood areas for the intervening days by linear interpolation. Thus, for each class, a daily time series of class total sap wood area was formed. The total daily transpiration (mm) for each class was then determined using

$$T_{\text{day}} = \frac{Q_{\text{mean}}}{A_{\text{ground}}} \sum_i Q\text{norm}_i\ \text{CSAtot}_i, \tag{5}$$

where CSAtot_i = total sap wood area for class i (m^2) and A_{ground} = ground area (m^2).

The uncertainty of the up-scaling from sap flow to stand transpiration was assessed using the standard error of the coefficients a and b in the estimation of Qnorm.

Stand transpiration is compared to Penman–Monteith potential transpiration using r_s and r_a adapted for willow [5]:

$$\lambda E = \frac{\Delta R_n}{\Delta + (1 + r_s/r_a)} + \frac{\rho C_p \delta e/r_a}{\Delta + (1 + r_s/r_a)}, \tag{6}$$

where R_n is net radiation (W/m^2), Δ is the slope of the temperature–saturation vapour pressure deficit curve (Pa/K), ρ is air density (kg/m^3), C_p is specific heat of the air (J/kg K), δe is vapour pressure deficit (Pa), r_a the aerodynamic resistance, here set to 50 s/m, r_s is the stomatal resistance per leaf area (s/m), determined by

$$r_s = \frac{1}{g_s \text{LAI}}, \tag{7}$$

where

$$g_s = \frac{R_s}{R_s + R_0} \frac{g_m}{1 + \delta e/a}, \tag{8}$$

where g_s = stomatal conductance per leaf area (s/m), R_s = incoming net radiation (W/m^2), g_m = maximum of g_s (s/m), R_0 = is a response coefficient for radiation (J/m^2 d) and a is a response coefficient for vapour pressure deficit (Pa).

2.2.6. WUE and RUE

Stand WUE for each willow clone and treatment was estimated from the ratio between produced biomass and transpiration amount over the measurement period, following Lindroth et al. [17], although here only including stem biomass production:

$$\text{WUE} = \Delta W_s/T, \tag{9}$$

where ΔW_s = total stem biomass production (g DS/m^2) and T = total transpiration rate (kg/m^2).

RUE for each clone and treatment was estimated from the ratio between produced stem biomass production (g DS/m^2) and the amount of accumulated APAR (mol/m^2) for the measurement period [27,28]:

$$\text{RUE} = \Delta W_s/\text{APAR}. \tag{10}$$

APAR was estimated at stand level using Beers Law:

$$\text{APAR} = \text{PAR}_{\text{above}}(1 - e^{-k\text{LAI}}), \tag{11}$$

where $\text{PAR}_{\text{above}}$ corresponds to the cumulated PAR above canopy and the extinction coefficient (k) that was set to 0.5 according to Eckersten [29]. The uncertainty of the estimated RUE was tested for k ranging from 0.4 to 0.6.

3. Results

3.1. Weather conditions during measurement period

The weather conditions during the experimental season are shown in Fig. 1. Compared to the normal period 1961–1990, the first half of the summer was sunny and dry with high temperatures. At the end of June, a rainy period started, with daily air temperatures around 15–18 °C. The average temperature did not deviate much from the normal period during the second half of the summer, while precipitation and global radiation was slightly lower than normal.

3.2. Plant development

In the start of the growing season, Tora and Loden had thicker but fewer stems than the other clones (Table 2). There was also a large variability in tree heights between clones, with taller stems for Tora and Rapp and shorter for L78183 and Jorunn. The results from the RT treatment shows that Tora performed best concerning biomass production during the growing season 2000, followed by

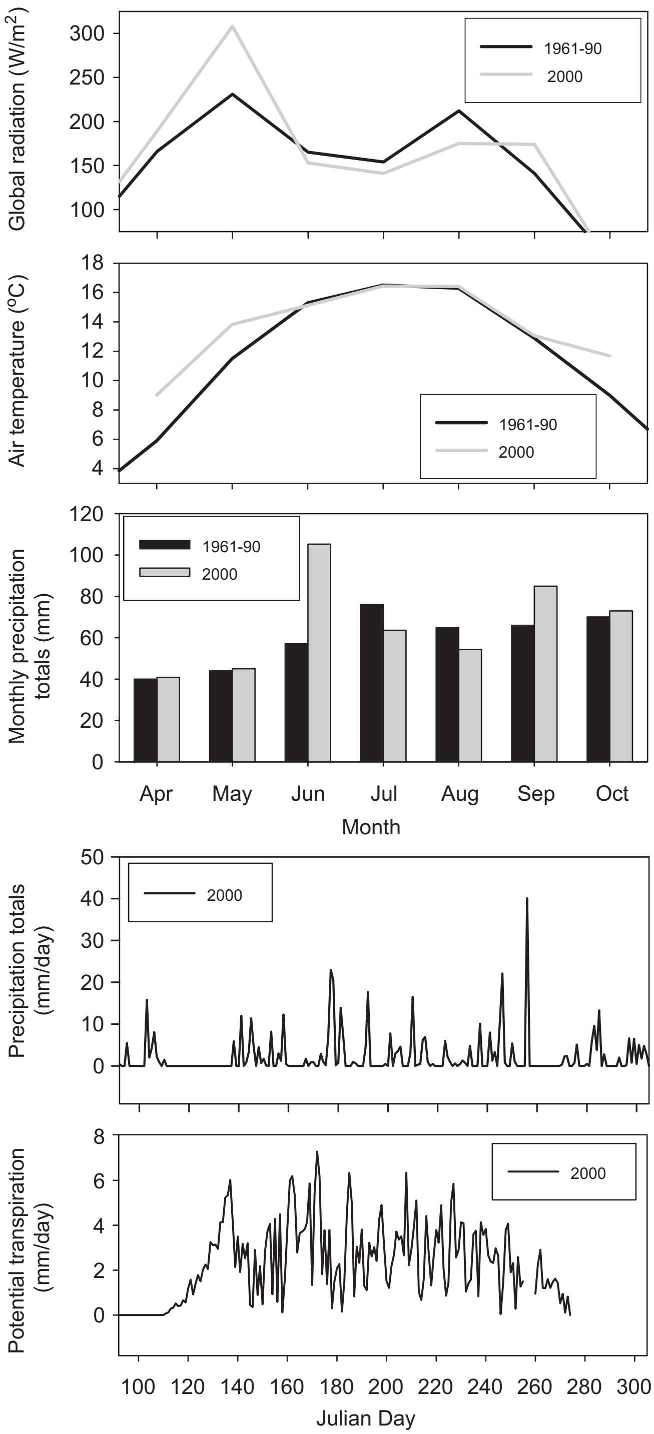

Fig. 1. Climate conditions at the site during the growing season and for the normal period 1961–1990. From top to bottom are monthly mean global radiation, monthly mean air temperature and monthly precipitation totals, daily precipitation totals and Penman–Monteith potential transpiration for willow.

Loden, Jorr and Rapp, that all performed better than the reference clone, L78183 (Fig. 2). Jorunn had clearly lower initial biomass and the production was also lower than for the other clones. For the plants in the DT, the production was lower for all clones than for the RT treatment except for Jorr that had approximately the same production result for both treatments. The growth of the clones during the growing season 2000 was clearly dependent on the initial biomass, with $r = 0.87$ for all clones and treatments, although this value is highly affected by the high production of Tora at RT and low values of Jorunn for both treatments (Fig. 3).

Table 2
Initial stem biomass, diameter and height in April 2000

Clone	Initial stem biomass (mg/ha)		Diameter (mm) (average/max)	Stem height (m)	Soil WC (mean volume %)	
	RT	DT			RT	DT
L78183	17.0	10.3	14/25	4.5	29.4	25.2
Jorr	22.3	12.6	17/30	5.3	25.9	23.5
Jorunn	13.3	3.8	13/28	4.3	26.3	25.0
Loden	21.6	14.6	18/35	5.1	22.2	22.4
Rapp	16.4	11.9	15/25	6.1	26.8	22.4
Tora	32.6	20.9	22/40	6.6	25.6	19.0

Soil water content corresponds to the average value of 20 June–30 September 2000.

The LAI followed the expected time development, except for Rapp (Fig. 4). Several of the clones, especially Tora, decreased in LAI between day 181 and day 195 (end of June to mid-July) due to leaf fall, probably caused by the drought before the end of June. The correlation between LAI and biomass production is low for the respective treatments as well as for all clones and treatments taken together (Fig. 3). For RT, L78183 and especially Loden had a very high LAI but did not perform much better than the other concerning growth. The production of Tora at RT is high despite low LAI and the production decreases rapidly with a small change in LAI, indicating that something else than leaf area affects the stem growth. Loden shows the opposite behaviour with small change in production for a large decrease in LAI.

3.3. Transpiration

3.3.1. Total stand transpiration

The estimated stand transpiration range between 100 and 325 mm for the 5 months, to be compared to an average precipitation of about 300 mm (1961–1990) and 350 mm during year 2000 for the same months (Fig. 1). The measured stand transpiration is far below the total Penman–Monteith potential transpiration, lying around 400–450 mm for the different willow clones. The transpiration rates are generally lower for DT than RT, except for Rapp. The uncertainty is less than 5% for all clones except Jorunn and L78183 (<10%).

Jorr at RT had the highest transpiration rates per unit ground area which is remarkable as neither the LAI is especially high compared to the other clones and nor is the

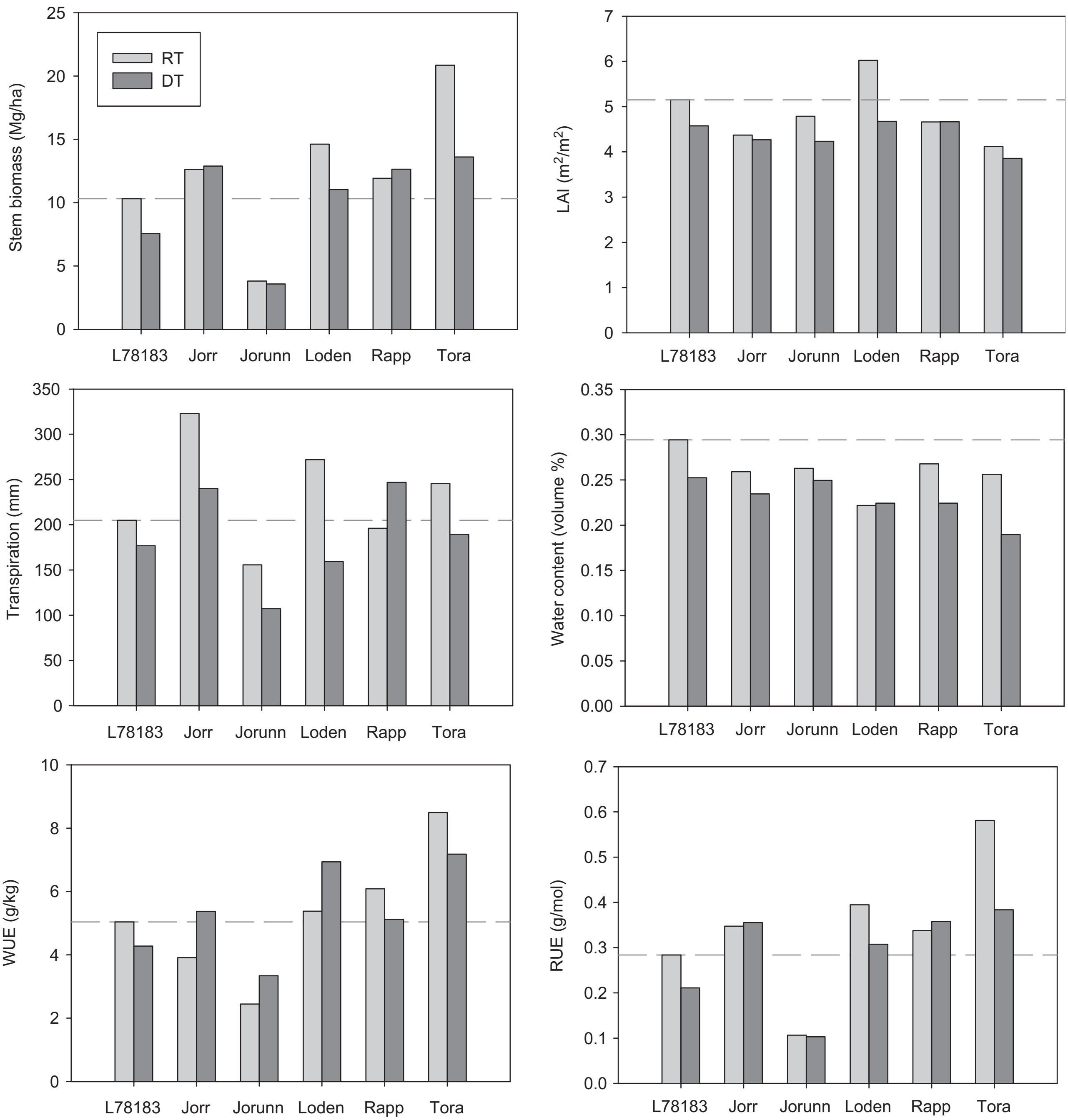

Fig. 2. Stem biomass production, LAI, transpiration, soil water content, WUE and RUE estimated for May–September 2000 for all willow clones and treatments. Hatched line shows level of reference clone, L78183.

standing stem biomass. The transpiration rate for Jorr at DT is lower than at RT but still high. Loden and Tora at RT had higher transpiration rates than the reference clone, which is reasonable compared to the amount of standing stem biomass. For RT and DT separately, as well as for all clones and treatments together, the correlation between LAI and transpiration is low. The transpiration rate decreases with LAI for both RT and DT for most of the clones, but the rate of decrease of transpiration varies with clone.

3.4. WUE and RUE

Average RUE for all clones and treatments is 0.31 g/mol. All clones and treatments have higher RUE than the reference clone except for Jorunn (Fig. 2). For the reference clone, L78183, Loden and Tora, RUE is lower for DT than RT. These effects mostly originate from the stem production for both RT and DT. The LAI and APAR seem to have had a minor effect on RUE (Fig. 3). The uncertainty in RUE, originating from the uncertainty in the extinction

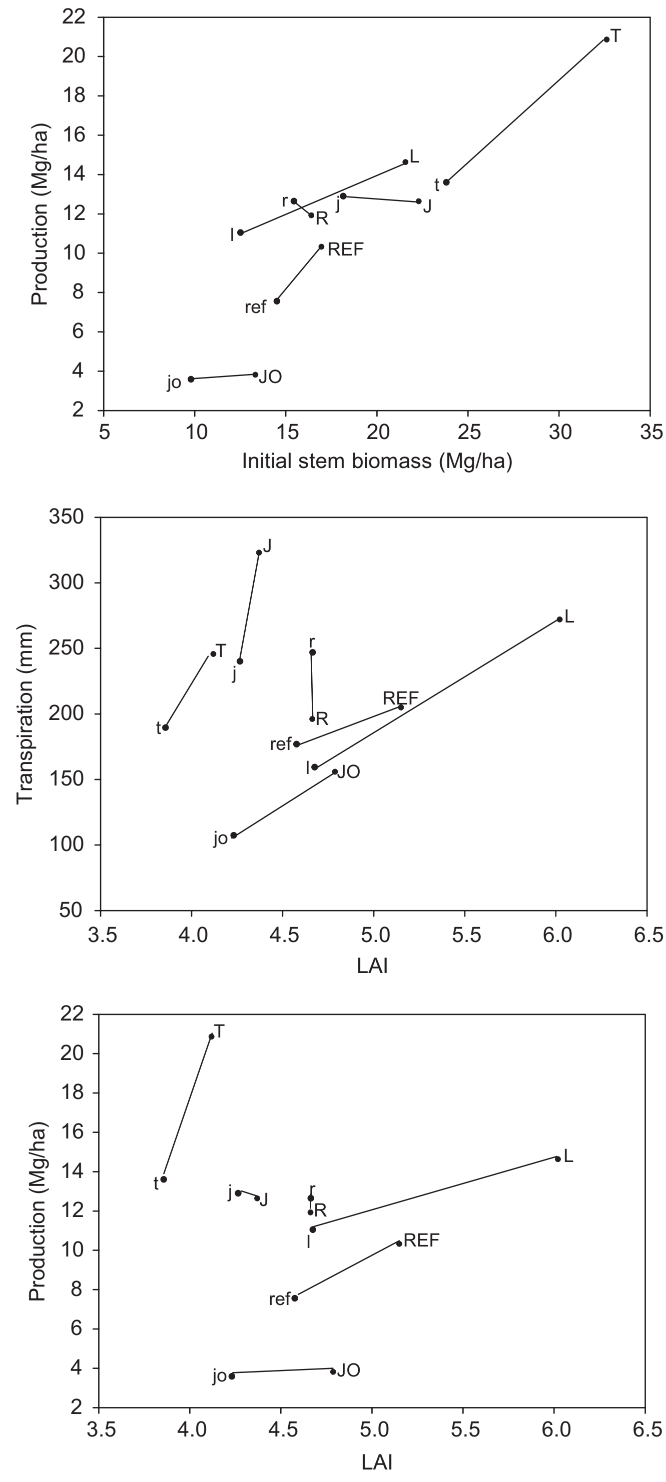

Fig. 3. Correlation between some of the observed variables. Top to bottom: initial stem biomass versus production during growing season 2000, LAI versus transpiration, LAI versus production. Upper case is RT, lower case is DT. REF: reference clone L78183, J: Jorr, JO: Jorunn, L: Loden, R: Rapp and T: Tora.

coefficient of the APAR estimations, lies around 10% of the estimated RUE.

Average WUE of all clones and treatments is ca. 5.3 g/kg. WUE at RT is higher than for the reference clone for Rapp, Tora and Loden, with exceptionally high rates for Tora (Fig. 2). The low values for Jorr at RT reflect the high transpiration rates. WUE increases for Jorr, Jorunn and Loden at DT compared to RT, corresponding to a larger difference in transpiration between RT and DT than for stem biomass production. Thus, the reduced water availability has a larger effect on the transpiration rates than stem biomass production. L78183 and Tora both decrease more in stem biomass production than transpiration rates. The uncertainty in WUE, originating from the uncertainty in the up-scaling of the sap flow to stand transpiration, is less than 5% for all clones except Jorunn and L78183 (<10%).

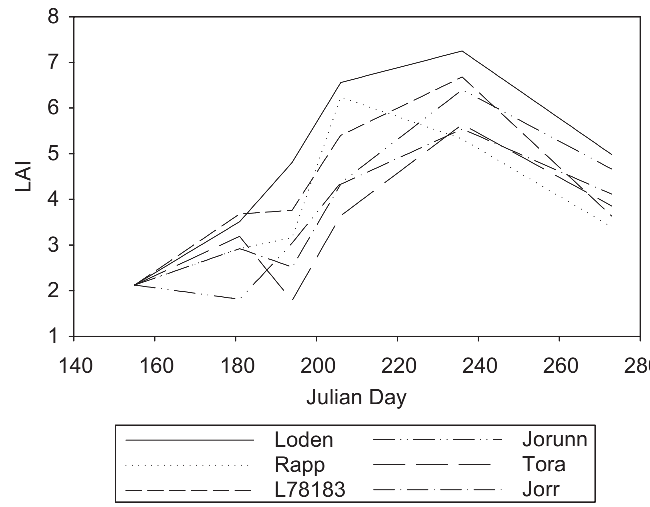

Fig. 4. LAI development for the six willow clones under normal treatment 2000.

4. Discussion

For all clones and treatments, the transpiration rates, including uncertainty, were far below the Penman–Monteith potential transpiration for willow at the site and rather in accordance with precipitation totals. This was during a season of fairly normal weather for southern Sweden. Compared to irrigated plantations, the observed rate was fairly low. It has been shown that willow can transpire twice as much in Sweden [5,7] and three times as much in UK although observations by Hall et al. [26] show that for *S. burjatica*, dry episodes clearly affects the transpiration rates.

The expected growth in southern Sweden, at average climate conditions [4], is in accordance with our observed production of 11.3 mg/ha. Compared to other studies, depending on climate and management (plant spacing, irrigation, fertilisation, etc.), a production of 10–20 mg/ha could be expected [30–32]. Thus, the production on average, despite low precipitation and soil water recharge, is acceptable.

Compared to other studies, the average WUE for all clones and treatments are somewhat high, which may depend on clonal variability in WUE in general or variability in allocation patterns. Lindroth and Ciencala [18] estimated long-term WUE to 6.3 g/kg transpired water for a *S. viminalis* stand (clone 77-683) at Ultuna, Sweden, although this includes whole plant biomass accumulation. For stem WUE, figure should be reduced to 60% according to allocation patterns found by Rytter [33]. Thus, the observed values in this study are rather high. Rytter used L78183 that may have a different allocation pattern than the newer clones. Nevertheless, WUE for L78183 lies around 5 g/kg, which is still quite high including the uncertainty of 10% of the estimated WUE.

The average RUE was 0.31 g/mol, which is reasonable compared to Eckersten [29] who estimated RUE to 0.43 g/mol in western Sweden. Using a conversion factor of 3.4 mol/MJ [29], the results lies around 1 g/MJ on average, somewhat lower than found by Bullard et al. [30] 1.33–1.82 g/MJ for a similar planting density in UK. The deviations may depend on the different estimations of the extinction coefficient, k. They used an extinction coefficient 0.2–0.5, based on observations in 2-year-old plantations, thus younger than the plantation studied here. We used observed values by Eckersten [29] of $k = 0.5$. Values ranging from $k = 4$ to 6 lead to $\pm 10\%$ difference in the estimated APAR. Despite this uncertainty, there is a clear difference in RUE between the clones and treatments.

Although these figures indicate that the growth as well as the efficiency in the use of water and light on average seems to be reasonable, despite low water availability, there is a large variability between clones. Tora performs best concerning all parameters; stem growth, WUE and RUE for both RT and DT, even though the difference between RT and DT is larger than for the other clones. Generally, all clones, except for Jorunn, seem to be better off concerning biomass production, WUE and RUE than the reference clone. Soil water content does not seem to have limited the transpiration rates and growth compared to the reference clone. Jorr, Jorunn and Loden also seem to be able to cope with the reduced water availability with increase in the water use efficiency.

For all clones, the reduction in RUE does not seem to be seriously affected by the lower LAI of DT compared to RT. RUE is more connected to the stem growth. This concerns especially Tora, with very little difference in LAI and with a similar pattern for WUE. WUE decrease as production decrease more than transpiration rate, instead of the expected increase in WUE from lower transpiration rates as shown by Jorr, Jorunn and Loden. This indicates that the RT may affect the allocation pattern. Nevertheless, Weih [34] and Weih and Nordh [11] reported a sensitivity of Tora for dry conditions. It should also be noted that as the extinction coefficient might vary more than estimated in this study, as shown by Bullard et al. [28] leading to a larger uncertainty in the result.

In this study, the difference in productivity and the efficiency in radiation and water use for field-grown clones of willow is evaluated at stand level. The results show that the sap-flow measurements, in combination with measurements of meteorological parameters, growth and LAI, can be successfully used to analyse the effect of water availability of the different willow clones grown under natural conditions. Nevertheless, using sap-flow techniques, the large number of stems and the variability in stem sizes on each stool makes the representativeness of the measured stems essential. A high amount of measurements is required as well as investigations on the frequency distribution of the stem sizes. A dependence of sap-flow density on stem diameter was reported by Ciencala and Lindroth [15] and Hall et al. [26]. It is evident from Table 1 that this relationship varies with willow clone, which indicates a hidden relationship with leaf area. Willow clones with thinner stems may have a higher leaf area/stem thickness ratio. This illustrates the importance of using differential equations when up-scaling stem sap-flow density to stand transpiration. Frequent biometry measurements are also needed to assess the sap wood area distribution as well as total sap wood area and their changes over time.

5. Conclusions

The stand productivity and the efficiency in light and water use under water limiting conditions were evaluated for field-grown willow clones. The results show that:

1. On average, the transpiration is low over the season compared to Penman, clearly affected by the water availability. Nevertheless, the stem growth as well as WUE and RUE are reasonable compared to other studies. Mean WUE is somewhat high while mean RUE is slightly low compared to other studies. It seems, thus, as the willow clones generally adapt well concerning WUE to the water shortage, which leads to a reduced ability to utilise PAR for stem growth.
2. Generally, all clones, except for Jorunn, seem to be better off concerning biomass production, WUE and RUE than the reference clone. Jorr, Jorunn and Loden also seem to be able to cope with the reduced water availability with increase in the water use efficiency.
3. Tora performs significantly better than the other clones concerning both growth and efficiency in light and water use. The effect of the RT on stem growth shows sensitivity to water availability. The reduced stem growth could be due to a change in allocation patterns.

Acknowledgements

This work was supported by the Swedish Energy Agency. Alexander Sedletski is thanked for programming and technical assistance during the fieldwork.

References

[1] Christersson L. High technology biomass production by Salix clones on a sandy soil in southern Sweden. Tree Physiology 1986;2:261–72.

[2] Sirén G. Energiskogsodling. Nämnden för energiproduktionsforskning, Stockholm. Rapport NE 1889 1983;11:255.

[3] Rosenqvist H, Roos A, Ling E, Hektor B. Willow growers in Sweden. Biomass and Bioenergy 2000;18:137–45.

[4] Lindroth A, Båth A. Assessment of regional willow coppice yield in Sweden on basis of water availability. Forest Ecology and Management 1989;121:57–65.

[5] Grip H, Halldin S, Lindroth A. Water use by intensively cultivated willow using estimated stomatal parameter values. Hydrological Processes 1989;3:51–63.

[6] Lindroth A, Iritz Z. Surface energy budget dynamics of short-rotation willow forest. Theoretical and Applied Climatology 1993;47: 175–85.

[7] Persson G, Lindroth A. Simulating evaporation from short-rotation forest; variations within and between seasons. Journal of Hydrology 1994;156:1–4.

[8] Niemczynowicz J, Linderson M-L, Olsson J, Bärring L. Regn i Skåne—Karakterisering av nederbörden i Skåne baserad på 234 dygnsmätare. Report no 3163, Department of Water Resources Engineering, Lund Institute of Technology, University of Lund, Sweden, 1993 [in Swedish].

[9] Åhman I, Larsson S. Genetic improvement of willow (Salix) as a source of bioenergy. Norwegian Journal of Agricultural Sciences 1994;(Suppl. 18):47–56.

[10] Larsson S. Genetic improvement of willow for short-rotation coppice. Biomass and Bioenergy 1998;15(1):23–6.

[11] Weih M, Nordh NE. Characterising willows for biomass and phytoremediation: growth, nitrogen and water use of 14 willow clones under different irrigation and fertilisation regimes. Biomass and Bioenergy 2002;23(6):397–413.

[12] Grelle A, Lindroth A. Eddy-correlation system for long term monitoring of fluxes of heat, water vapour and CO_2. Global Change Biology 1996;2:297–307.

[13] Telenius B, Verwijst T. The influence of allometric variation, vertical biomass distribution and sampling procedure on biomass estimates in commercial short-rotation forests. Bioresource Technology 1995;51: 247–53.

[14] Smith DM, Allen SJ. Measurement of sap flow in plant stems. Journal of Experimental Botany 1996;47(305):1833–44.

[15] Ciencala E, Lindroth A. Gas-exchange and sap flow measurements of *Salix viminalis* trees in short-rotation forest. I: transpiration and sap flow. Trees 1995;9:289–94.

[16] Verwijst T, Telenius B. Biomass estimation procedures in short rotation forestry. Forest Ecology and Management 1999;121(1–2): 137–46.

[17] Lindroth A, Verwijst T, Halldin S. Water-use efficiency of willow: variation with season, humidity and biomass allocation. Journal of Hydrology 1994;156:1–19.

[18] Lindroth A, Ciencala E. Water use efficiency of short-rotation *Salix viminalis* at leaf, tree and stand scales. Tree Physiology 1996;16:257–62.

[19] Ager A, Rönnberg-Wästljung A, Thorsén J, Sirén G. Genetic improvement of willows for energy forestry in Sweden. Report 43, Swedish University of Agricultural Sciences, Uppsala, 1986. 47pp.

[20] Topp GC, Davis JL, Annan AP. Electromagnetic determination of soil water content: measurements in coaxial transmission lines. Water Resources Research 1980;16:574–82.

[21] White J. The allometric interpretation of the self-thinning rule. Journal of Theoretical Biology 1981;89:475–500.

[22] Swanson RH. Significant historical developments in thermal methods for measuring sap flow in trees. Agricultural and Forest Meteorology 1994;72:113–32.

[23] Granier A. A new method of sap flow measurement in tree stems. Anales des Sciencies Forestieres 1985;42(2):193–200.

[24] Granier A. Evaluation of transpiration in a Douglas-fir stand by means of sap flow measurements. Tree Physiology 1987;3:309–20.

[25] Lundblad M. Variation in forest water fluxes at local scale. Doctoral thesis, SLU, 2001, p. 189.

[26] Hall RL, Allen SJ, Rosier PTW, Hopkins R. Transpiration from coppiced poplar and willow measured using sap-flow methods. Agricultural and Forest Meteorology 1998;90(4):275–90.

[27] Cannell MGR, Milne R, Sheppard LJ, Unsworth MH. Radiation interception and productivity of willow. Journal of Applied Ecology 1987;24(1):261–78.

[28] Bullard MJ, Mustill SJ, Carver P, Nixon PMI. Yield improvements through modification of planting density and harvest frequency in short rotation coppice Salix spp. 2: resource capture and use in two morphologically diverse varieties. Biomass and Bioenergy 2002;22(1): 27–39.

[29] Eckersten H. Light penetration and photosynthesis in a willow stand. In: Perttu KL. (Ed.). Ecology and management of forest biomass production systems. Report 15, Department of Ecology and Environmental Research, Swedish University of Agricultural Sciences, Uppsala, 1984. p. 29–45.

[30] Bullard MJ, Mustill SJ, McMillan SD, Nixon PMI, Carver P, Britt CP. Yield improvements through modification of planting density and harvest frequency in short rotation coppice Salix spp. 1: yield response in two morphologically diverse varieties. Biomass and Bioenergy 2002;22(1):15–25.

[31] Heinsoo K, Sild E, Koppel A. Estimation of shoot biomass productivity in Estonian Salix plantations. Forest Ecology and Management 2002;170(1–3):67–74.

[32] Labrecque M, Teodorescu TI. Field performance and biomass production of 12 willow and poplar clones in short-rotation coppice in southern Quebec Canada. Biomass and Bioenergy 2005;29(1):1–9.

[33] Rytter R-M. Biomass production and allocation, including fine-root turnover, and annual N uptake in lysimeter-grown basket willows. Forest Ecology and Management 2001;140:177–92.

[34] Weih M. Evidence for increased sensitivity to nutrient and water stress in a fast-growing hybrid willow compared with a natural willow clone. Tree Physiology 2001;21(15):1141–8.