Spatial variation in above-ground growth in unevenly wastewater-irrigated willow *Salix viminalis* plantations

Pär Aronsson a, * Katrin Heinsoo b, Kurth Perttu a, Kenth Hasselgren c

**Abstract**

In several Swedish wastewater treatment plants, an improved level of water treatment has been achieved through irrigation of short-rotation willow (*Salix viminalis*) coppice (SRWC) with secondary or tertiary treated wastewater. The spatial variation in above-ground growth in two unevenly wastewater-irrigated SRWC fields in southernmost Sweden was measured during 3 consecutive years. Wastewater was distributed on the soil surface through pipes with emitters spaced at distances varying from 10 to 21 m. During the first year of irrigation, a very marked gradient in growth developed, with stools (i.e. resprouted stubs) standing within 2 m of wastewater emitters growing several times faster than those standing 5 m or more away. This situation prevailed after three growing seasons with wastewater irrigation, indicating that any redistribution of plant roots towards the emitters was insufficient for a spatial levelling of the growth. We conclude that, in order to promote growth and fully utilize the treatment potential of SRWC, wastewater should be applied fairly evenly, i.e. through emitters at spacings of less than 5 m. © 2002 Published by Elsevier Science B.V.

**Keywords:** Coppice; Growth response; Irrigation; Wastewater treatment; Willows

1. Introduction

1.1. Background

Large efforts have been made in the Baltic region to reduce the release of N and P to the Baltic Sea, and thereby improve the water quality. In Sweden, wastewater treatment plants have encountered new and more rigorous demands for nitrogen removal efficiency (Anon., 1988, 1991, 1997). The conventional way of achieving this is to enhance denitrification in the treatment plants, which usually requires substantial investments (Balmér and Mattsson, 1993). However, improved wastewater treatment through irrigation of willow plantations is a potentially cost-efficient alternative to 'engineered' methods (Rosenqvist et al., 1997), and has been adopted in several Swedish wastewater treatment plants. Moreover, such 'wil-
low vegetation filters’ enable recycling of plant nutrients and water.

In Sweden, about 18 000 ha of arable land is presently being used for short-rotation willow coppice (SRWC) mainly consisting of different clones of *Salix viminalis* (L.) and *Salix dasyclados* (Wimm.). Planting is usually performed with cuttings in a double-row system with a spacing of 0.75 and 1.5 m, respectively, between the rows and 0.5–0.6 m within the row, resulting in a plant density of 13 700–17 800 plants/ha. The willows are harvested (coppiced) in wintertime every 3–5 years. At harvest, the stems are cut and chipped by a harvesting machine and used as a fuel in district heating plants. After harvest the stubs, hereafter referred to as stools, resprout and usually reach high growth rates even in the first year. To increase biomass production, Swedish farmers are advised to fertilize the SRWC with nitrogen at rates which average around 80 kg N/ha year (Ledin et al., 1994). Irrigation is not economically viable, although the high water demand of SRWC is well documented (e.g. Grip et al., 1989; Lindroth et al., 1994).

When establishing a willow vegetation filter for wastewater treatment, the main cost is for the irrigation system including pumps and distribution pipes (Rosenqvist et al., 1997). For sanitary reasons, spray or trickle irrigation is avoided in Sweden (Stenström, 1996; Carlander, 2002) and therefore different types of drip irrigation systems are used. One such system (RMV Bioirrigation) comprises 32-mm PEM pipes laid in the plant rows (in order not to obstruct harvest) at varying distances from each other. The pipes have emitters every 10 m, and each emitter supplies a ground area that is in the order of 100 m$^2$, and thus, at each emitter the hydraulic load is very high. As a consequence, above-ground growth is found to be very unevenly distributed initially within fields irrigated using this system. Since roots of broad-leaved trees are known to grow towards distant water and nutrient resources and proliferate there (Pregitzer et al., 1993; Mou et al., 1995), it was postulated that this variability in growth would decrease over time.

### 1.2. Objectives

The aim of our study was to quantify the spatial variation in above-ground growth of stools in two unevenly wastewater-irrigated willow plantations and to quantify the development of this variation over time. The hypotheses were:

1) Stool growth is affected by the distance to the nearest emitter of wastewater.

2) Stool growth is affected by orientation of plant rows.

3) The plantation area affected by wastewater application will increase over time.

Use of a model approach to produce a generalised estimate of growth and nitrogen treatment efficiency in unevenly wastewater-irrigated SRWC will be presented in a separate work.

### 2. Methods

#### 2.1. Experimental field sites

The measurements were conducted in two 10-ha willow vegetation filter systems at Bromölla and Kågeröd in southernmost Sweden. Field characteristics are shown in Table 1. On both fields, basket willow (*Salix viminalis*) was established using Swedish standard methods and machinery

<table>
<thead>
<tr>
<th>Site characteristics of the Bromölla and Kågeröd field trials</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Location</strong></td>
</tr>
<tr>
<td>Altitude</td>
</tr>
<tr>
<td>Mean air temperature</td>
</tr>
<tr>
<td>Mean annual precipitation</td>
</tr>
<tr>
<td>Soil type</td>
</tr>
<tr>
<td>Clay content (topsoil)</td>
</tr>
<tr>
<td>Depth of unsaturated zone</td>
</tr>
<tr>
<td>Planting year</td>
</tr>
<tr>
<td>Planting density</td>
</tr>
</tbody>
</table>
for soil preparation, planting and weed control. At Kågeröd, planting was made in 1995, whereas at Bromölla, planting was made in 1996 (Table 1). After the first growing season, the plants were cut back in order to promote sprouting and to speed up canopy closure. Due to insufficient weed control, the plants at the Bromölla field established poorly. All measurements were conducted in parts of the fields planted with the same clone ('Rapp' from Svalöf Weibull AB).

Irrigation systems of the RMV type described above were installed at both sites during spring 1997. Field irrigation at Bromölla started in June 1997 with tertiary treated wastewater (i.e. after phosphorus precipitation) from the local wastewater treatment plant. Irrigation of the field at Kågeröd started in May 1997 using secondary treated wastewater from the local wastewater treatment plant. Thus, at Kågeröd the plants had 1 more year for plant growth without influence from irrigation than at Bromölla. Irrigation rates and wastewater composition are shown in Table 2.

2.2. Sampling and calculations

In the Bromölla field, an experimental plot for biomass estimations was established in June 1997. Within the experimental plot, five wastewater emitters in a row were located (hereafter also referred to as ‘sampling points’). The irrigation system was rearranged so that the distance to the nearest adjacent irrigation pipe was 22 m and the distance between emitters in the row was 21 m. Within the Kågeröd field, irrigation pipes were laid out with varying distances between pipes (4.5–18 m) but with a fixed distance of 10 m between emitters in the row. Three of the five sampling sites at Kågeröd were located in a part of the field where the distance between pipes was 18 m. The other two sampling points were located in a part of the field where the distance between irrigation pipes was 11.25 m. Thus, in the Kågeröd field, the distance between the emitters was at least 10 m.

Biomass estimations were performed in February 1998, February 1999, and October 1999. At each sampling point, stools were measured in transects along and across the plant rows (Fig. 1). The transects crossed at the emitters at an angle of 90° (Bromölla) or 72° (Kågeröd). The difference was due to a small displacement of the plant rows that occurred during planting at Kågeröd, and adapting to this displacement significantly simplified the field work. The shoot dry weight (DW) of all living stools within the sections was estimated using a combination of destructive and non-destructive measurements (Verwijst and Telenius, 1999). The diameter of each living shoot was measured at 55 cm height using a calliper. Shoots of all diameter classes (approximately 30 shoots per site) were then harvested and dried at 80 °C until constant weight to obtain a two-parameter power function describing the relationship between shoot diameter and shoot DW:

\[
DW = b \times \text{Diameter}^c
\]

where \( b \) and \( c \) are parameters obtained by nonlinear regression using Sigma Plot® software.

The distance between each measured stool and the nearest emitter was measured with an accuracy of 0.05 m. The plant rows delineated distinct distance classes in a cross-row transect. Stools growing within the rows (i.e. in the row where the

<table>
<thead>
<tr>
<th>Table 2: Amounts and characteristics of wastewater used for irrigation of the willow plantations at Bromölla and Kågeröd</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual load of wastewater at each sampling site (m³)</td>
</tr>
<tr>
<td>Average daily load of wastewater at each sampling site (m³/d)</td>
</tr>
<tr>
<td>Average N-concentration (mg N-tot/l)</td>
</tr>
<tr>
<td>Average P-concentration (mg P-tot/l)</td>
</tr>
</tbody>
</table>
irrigation pipe was laid) were grouped into 1-m distance classes (0–0.99 m, 1.0–1.99 m, etc.). Thus, in the further presentation, distance refers either to the actual distance or the mean of upper and lower distance class limits.

For each sampling year, field and direction, stool DW was plotted against distance from the nearest emitter of wastewater. Subjectively, the stools most distant from the emitters (i.e. approximately more than 4–6 m from the emitters) and seemingly unaffected by wastewater irrigation were selected as reference. The relative DW of each stool was then calculated using the mean DW of the reference stools as the denominator. Linear regressions with distance as independent variable and relative stool DW as dependent variable were established. Differences ($P < 0.05$) among the slope of the regression lines were tested using pooled variance and the degrees of freedom approximated according to Montgomery (1983). The risk of mass significance was compensated for using the Sidak $t$-test.

3. Results

Stool growth was highly dependent on the distance from the stool to the nearest emitter (Figs. 1 and 2). At the Bromölla site in particular, the growth rate of the stools close to the emitters was several times higher than that of the reference stools (i.e. the stools more than 5.5 m from the emitters) (Fig. 2). As shown by the regression lines (Fig. 2), between 1997 and 1999 the diameter of the ‘islands’ of high growth at Bromölla did not increase. However, there was a tendency, although not significant, for the differences in relative stool DW to be smaller in 1999 than in 1997 (Fig. 2). At the 1999 sampling, the differences in slope of the regression lines between sampling transects across and along rows were not significant. At the Kageröd site, the differences in relative stool DW between stools close to and distant from the emitters were much less pronounced than at the Bromölla site (Fig. 2). There was a slight tendency of levelling of the distance dependency along the irrigation pipes between 1997 and 1999. However, across the pipes there was no sign of such a levelling. At both sites wastewater application positively affected stool growth at greater distances along the irrigation pipes than across (Fig. 2). Thus, at a certain distance plants growing along the pipes had a higher growth than stools growing across pipes and plant rows.

4. Discussion

During 1997, i.e. the first year of irrigation, a clear gradient in stool growth developed in both fields. This was particularly apparent at the
Bromölla site. The stools standing within 1 or 2 m from the emitters grew approximately four times faster than the stools growing 5 m or more away (Fig. 2). This difference prevailed during the two following growing seasons, resulting in a very unevenly distributed stool weight in autumn 1999. At the Kaågeröd site, there was also a marked distance dependency, but this was by no means as clear as at the Bromölla site (Fig. 2). There are several possible explanations for the differences between the two sites. Firstly at the Kaågeröd site, irrigation started 2 years after planting, leaving two full growing seasons for plant establishment and root exploration of the soil. Second, at the Kaågeröd site, the overall stool growth was much higher than at the Bromölla site. This was probably due to less weed competition (which was severe at the Bromölla site), but possibly also to a higher natural soil fertility and water availability as indicated by the higher precipitation at

Fig. 2. Class-averaged relative stool dry weight (DW) as a function of distance from the nearest emitter of wastewater after 1997 (○, --) and 1999 (●, —) growing seasons respectively, in Bromölla and Kaågeröd. The reference lines were calculated as the mean of the most distant classes, i.e. those seemingly unaffected by irrigation, and they correspond to absolute plant weights of 57 and 613 g/plant (across), and 90 and 799 g/plant (along) for 1997 and 1999, respectively at Bromölla. The corresponding absolute plant weights at Kaågeröd were 507 and 1191 g/plant (across), and 878 and 1815 g/plant (along) for 1997 and 1999, respectively. Error bars indicate S.E.
Kågeröd (Table 1). It is a realistic assumption that application of wastewater has a lower impact on growth at a naturally fertile site.

We hypothesized that the spatial variability in stool growth would decrease over time as a result of root system redistribution. It is known that roots tend to find water and nutrient resources and proliferate there (Strong and La Roi, 1985; Pregitzer et al., 1993; Robinson, 1994; Kätterer et al., 1995; Mou et al., 1995; Dickman et al., 1996). Accordingly, we assumed that the diameter of the ‘green islands’ of high stool growth would increase over time. This was apparently not the case. In fact, the diameters of the ‘green islands’ were practically unaltered from the first to the third growing season with wastewater irrigation (Fig. 2). This may be attributable to root competition. Plants that had access to wastewater were able to grow faster, and were probably also able to efficiently compete (in the root zone) with plants more distant from the emitters. The much taller shoots of stools close to the emitters might also have somewhat shaded the adjacent but shorter shoots of stools more distant from the emitters.

At the Bromölla site there was a tendency for direction dependency (Fig. 2). At a certain distance from the emitters, the stools growing along the irrigation pipes, i.e. within the double row in which the irrigation pipe was laid, tended to grow faster than stools growing perpendicular to (across) the irrigation pipes. Although it was not measured, a realistic assumption would be that neighbouring stools in one direction would tend to reduce root growth in that direction (e.g. Brisson and Reynolds, 1994; Mou et al., 1997). Thus, beforehand we believed that the spatial arrangements of stools would give the opposite results to those actually obtained. An alternative explanation is called for, and a preferential distribution of wastewater in the soil could be such an explanation. When establishing and managing a SRWC, tractor-mounted aggregates are run along the plant rows. In addition, the irrigation pipes are subject to shrinking and elongation due to temperature variations. This possibly resulted in a small soil-surface depression underneath the pipes. One could therefore speculate that there were structures facilitating surface or sub-surface flow of wastewater along the irrigation pipes.

5. Conclusions

Beforehand, we hypothesized that in fields planted with short-rotation willow coppice (SRWC) and unevenly supplied with wastewater that: (1) stool growth would be affected by the distance to the nearest emitter of wastewater; (2) stool growth would be affected by the orientation of plant rows; and (3) the plantation area affected by wastewater application would increase over time. The results from biomass estimations during 3 consecutive years support the first hypothesis, but not the other two hypotheses. The direction somewhat influenced the stool growth, but in the opposite way than expected. This was probably due to preferential surface or sub-surface flow of wastewater along the plant rows. We could not detect any significant spatial levelling of the stool growth at the two experimental sites during the 3-year study.

As shown by Aronsson (2000), nitrogen retention in willow vegetation filters is correlated with the biomass productivity. Thus, in order to maximise the treatment efficiency in such systems high biomass productivity should be promoted. For this, high spatial variability in growth, as found in the present study, should be counteracted. Accordingly, the spatial distribution of wastewater should be fairly even, and the distance between wastewater emitters should be kept small, preferably less than 5 m. This would ensure a high and (spatially) fairly even growth, which would in turn promote high treatment efficiency.

Acknowledgements

This study was supported by grants from the Swedish National Energy Administration and by a scholarship from the Swedish Institute, which are gratefully acknowledged. We also thank R. Childs and E.-M. Fryk for carrying out most of the field work.
References


