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Published in:
Environmental Pollution

DOI:
10.1016/j.envpol.2009.10.003

2010

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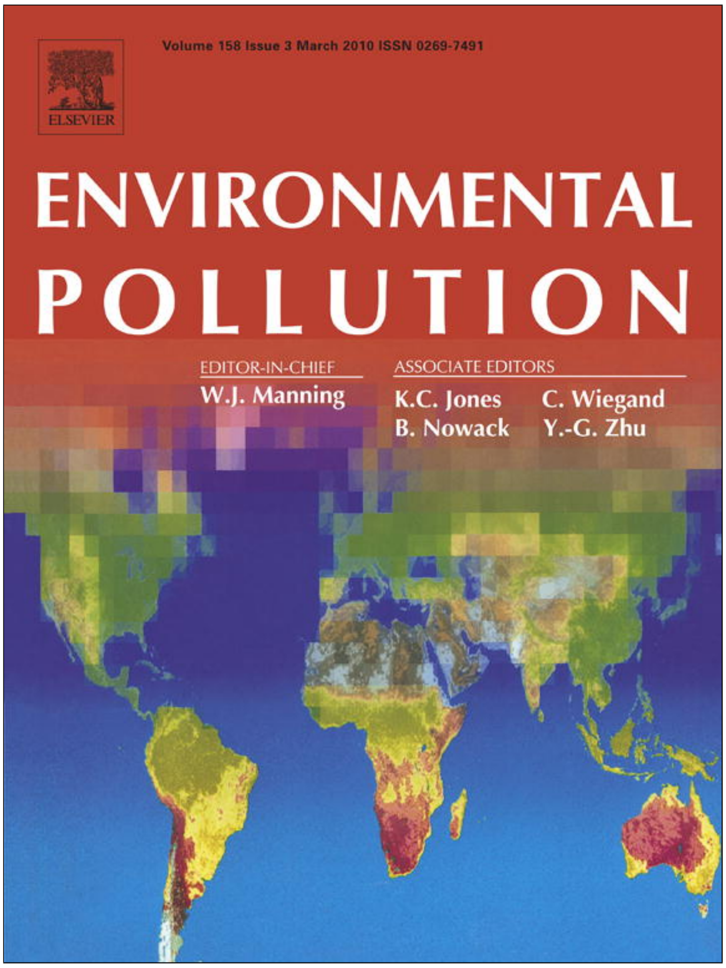
Volume 158 Issue 3 March 2010 ISSN 0269-7491
ELSEVIER
ENVIRONMENTAL
POLLUTION
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Environmental Pollution 158 (2010) 795–804

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

Treatment of landfill leachate by irrigation of willow coppice – Plant response and treatment efficiency

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Short-rotation willow coppice was successfully used for treating a strong landfill leachate in central Sweden over three years.

ARTICLE INFO

Article history:
Received 14 May 2009
Received in revised form
29 September 2009
Accepted 4 October 2009

Keywords:
Salix
Toxicity
Nitrogen
Leaching
Heavy metals
Water balance
Groundwater

ABSTRACT

Landfill leachates usually need to be treated before discharged, and using soil–plant systems for this has gained substantial interest in Sweden and in the UK. A three-year field study was conducted in central Sweden to quantify plant response, treatment efficiency and impact on groundwater quality of landfill leachate irrigation of short-rotation willow coppice (*Salix*). Two willow varieties were tested and four irrigation regimes in sixteen 400-m^2 plots. The willow plants did not react negatively, despite very high annual loads of nitrogen ($\leq$2160 kg N/ha), chloride ($\leq$8600 kg Cl/ha) and other elements. Mean annual growth was 1.5, 9.8 and 12.6 tonnes DM/ha during years 1–3. For one of two willow varieties tested, relative leaf length accurately predicted growth rate. Irrigation resulted in elevated groundwater concentrations of all elements applied. Treatment efficiency varied considerably for different elements, but was adequate when moderate loads were applied.

1. Introduction

Landfills usually generate leachate water as a result of surplus precipitation and degradation of organic waste within the landfill. Such leachate usually contains the entire spectrum of elements present in the landfill, but the feature that distinguishes it from conventional wastewater is the generally very high concentration of nitrogen and salts (Alker, 1999; Dimitriou, 2005). Swedish landfill leachate typically contains some 200–400 mg/L of nitrogen, mainly in the form of ammonium but also organically bound, and sodium chloride in concentrations typically in the range 800–1800 mg/L (Öman et al., 2000). In Sweden, landfill leachate must be treated before being discharged, and mixing with conventional wastewater and treatment in conventional wastewater treatment plants is common practice. However, different types of 'ecological engineering' treatment methods, including constructed wetlands and irrigation of trees or perennial crops, have also been applied. The driving force behind this is partly economic considerations, and partly a search for more efficient treatment methods, as the chemical composition of landfill leachate makes it difficult to treat. In addition, current efforts to improve the quality of sewage sludge so that it can be used as fertiliser in agriculture are also forcing wastewater treatment operators to exclude landfill leachate from treatment plants.

In Sweden, short-rotation willow coppice (SRWC) for producing biomass for energy is a fully mechanised, commercial cropping system. The crop is relatively cheap to establish, grows rapidly and is harvested every 3–5 years. These properties, together with the fact that willow is a non-food and non-fodder crop, make it interesting for ecological engineering purposes. During the 1990s, several systems were established in Sweden for treating landfill leachate by irrigation of SRWC established either on restored parts of landfills or on adjacent arable fields (Aronsson and Perttu, 2001). Similar systems have been tested in the UK, USA, Poland and elsewhere (Bialowiec et al., 2007; Godley et al., 2004; Jones et al., 2006; Zalesny and Bauer, 2007). Some scientific studies on the treatment efficiency of such systems show promising results but variable efficiency (Alker, 1999; Dimitriou et al., 2006; Watzinger et al., 2006). Studies from the UK have reported toxicity symptoms in willow plants irrigated by landfill leachate, probably due to its high ionic strength (Stephens et al., 2000). In USA leachate treatment using different poplar (*Populus* spp.) species and varieties has been studied extensively, showing variable but generally high tolerance to landfill leachate (e.g. Zalesny et al., 2007).

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doi:10.1016/j.envpol.2009.10.003

In Swedish treatment systems using SRWC, plant die-back has been reported, possibly due to leachate irrigation (Dimitriou et al., 2003). It has been suggested that nutrient imbalances could also be the reason for such die-back, but this has not been scientifically proven. In a greenhouse pot experiment (Dimitriou and Aronsson, 2007), willow plants were found to be more sensitive to sodium as to chloride on a molar basis, and at quite moderate concentrations, i.e. clear negative effects were observed on the plants at concentrations of 200 mg/L for sodium and 600 mg/L for chloride. However, little is known about causes of plant damage in a field situation or about threshold values of total salinity, sodium or chloride concentrations limiting irrigation rates. In the present situation with a high degree of uncertainty concerning the effects of leachate irrigation, a method for quantifying the degree of stress caused by application of landfill leachate would be useful. One such method, based on leaf length measurements, has been reported by Dimitriou et al. (2003). In that (pot) study, relative leaf length was highly correlated with relative growth rate, which in turn is widely used as an estimator of plant stress.

In this paper, we report the results from a three-year field study on the consequences of intensive leachate irrigation of two willow varieties. The objectives of the study were to:

1. Quantify the effects on plant growth and possible negative impacts on the plants from leachate application.
2. Evaluate the usefulness under field conditions of easily measured indicators of plant stress caused by leachate irrigation.
3. Assess the effects of leachate irrigation on groundwater quality.
4. Quantify the treatment efficiency of SRWC for treatment of landfill leachate in terms of retention of different pollutants in the soil–plant system.

The study contributes with long-term data on performance of such treatment systems and suggests ways of monitoring the plant vitality and treatment efficiency, that do not involve high costs.

2. Materials and methods

2.1. Site and plants

The field trial was established on an arable field adjacent to a large, commercial landfill operated by Ragnsells Avfallsbehandling AB, Upplands-Bro, Sweden (59°33′08 N; 17°37′25 E). Data on precipitation and temperature during the experiment was obtained for the station Sätra gård, 12 km west of Högbytorp from the Swedish Meteorological and Hydrological Institute (SMHI) and are presented in Fig. 1. Precipitation was normal for the area during the study period, but winter temperatures were higher than normal. The soil was a heavy clay soil with 34–42% clay content, a humus content of 14–25% in the topsoil and a pH of 6.7.

The trial comprised sixteen 400-m^2 square plots divided into two blocks according to an assumed gradient in groundwater level (Fig. 2). Four treatments were applied (see below), each with two replicates for each of the two willow varieties tested. The experimental design was heavily dependent on practical considerations and this limited the options for randomisation. Thus, from a statistical viewpoint the setup did not involve "true" replicates, and the treatments were potentially confounded with gradients in the field.

On 18–19 May 2005, cuttings of two varieties of willow, *Tora* and *Gudrun*, were planted manually in a double-row system with 1.5 m distance between the double rows, 0.75 m between the rows in the double row, and with a spacing of 0.6 m between plants in the rows. This corresponds well with the way commercial willow plantations are established in Sweden. *Tora* is a hybrid between *Salix schwerinii* and *Salix viminalis*, and *Gudrun* is a pure *Salix dasyclados* variety with partly Russian origin, making it more frost-tolerant than *Tora*.

The field was prepared for planting during 2004 by chemical weed control (glyphosate) during autumn followed by ploughing. One week before planting, the soil was cultivated with a rotary cultivator. After planting, mechanical weeding was carried out repeatedly from June onwards. A sprinkler irrigation system was established in order to prevent drought damage before the onset of leachate irrigation. Drip irrigation pipes were laid out in every double row for distribution of the landfill leachate.

2.2. Treatments

Three different rates of landfill leachate irrigation and one control treatment were applied (Fig. 2). In each plot a set of groundwater pipes was installed for measurement of groundwater level and for sampling of superficial groundwater.

The landfill leachate water used for irrigation was pre-treated in a nitri/denitrification facility at the landfill site. The chemical composition of the leachate varied considerably during the experiment, partly due to the management and performance of the pre-treatment facility. The three levels of leachate irrigation corresponded to 1 (Treatment 1), 2 (Treatment 2), and 3 (Treatment 3) times the previously calculated mean precipitation deficit, i.e. the difference between normal precipitation and the estimated evapotranspiration during the summer period.

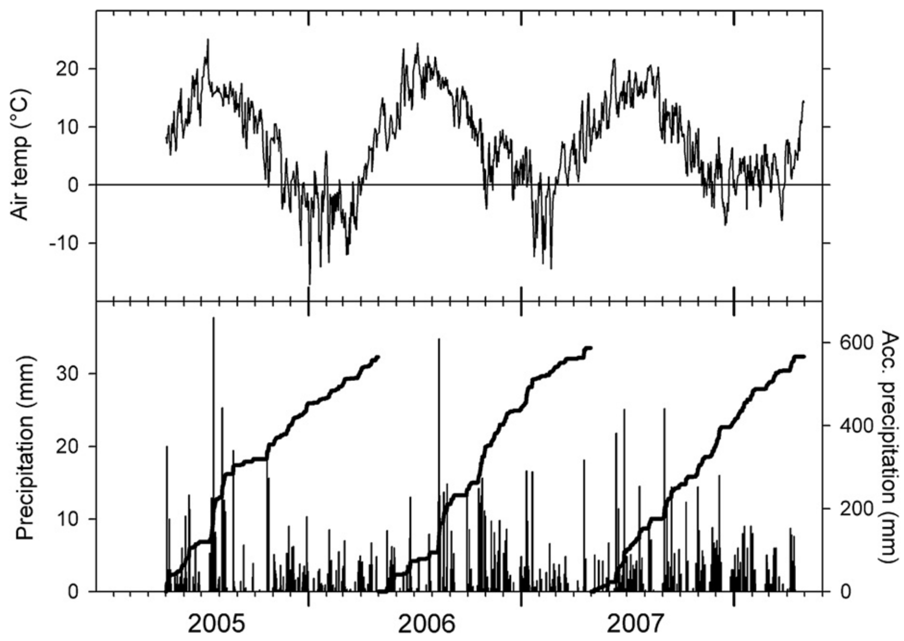

Fig. 1. Daily mean temperature (above) and daily and seasonal cumulative precipitation (below) for Sätra gård, central Sweden during 2005–2008.

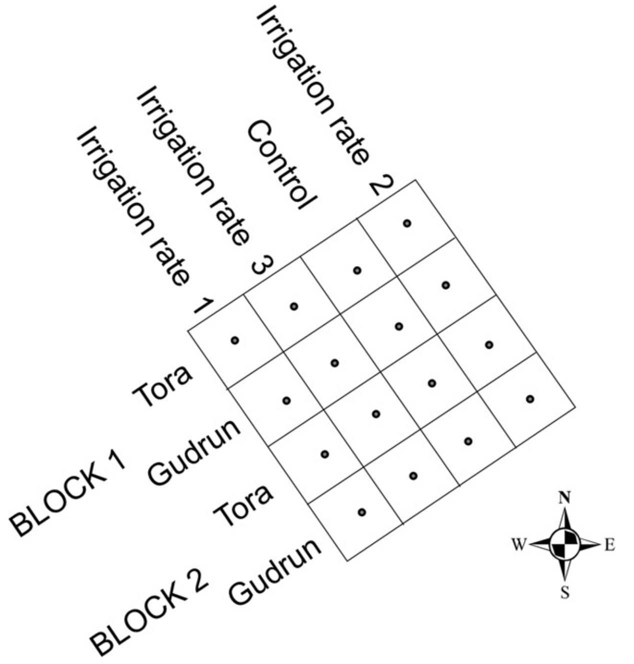

Fig. 2. Design of the field trial with block, willow variety, treatment and lines for soil resistivity measurements. Dots in the centre of each plot represent the positions of groundwater pipes. Before-hand, a gradient from NW to SE was assumed as regards depth of groundwater and subsoil properties.

Calculation of the precipitation deficit was based on mean precipitation data for Uppsala (40 km north of Upplands-Bro). Evapotranspiration was estimated using data from SRWC in the region presented by Persson and Lindroth (1994). The control (Ctrl) treatment was not irrigated in the first growing season (i.e. 2005), but during 2006 and 2007 it was irrigated with tapwater in amounts corresponding to the calculated mean precipitation deficit. The start and end of irrigation in each season and the cumulative irrigation loads are presented in Table 1. The concentrations of different elements in the leachate and the loads applied through irrigation are presented in Table 2.

2.3. Sampling and analyses

2.3.1. Groundwater measurements

Groundwater pipes were installed in the centre of each field-plot (Fig. 2) between 8 and 17 June 2005. Two holes were drilled, to a depth of 0.8 and 1.3 m, respectively, using an auger. PVC pipes with a diameter of 50 mm and with slits from the bottom up to 0.5 m from the soil surface were installed in the holes. In order to prevent clogging, the base of each pipe was fitted with a 10-μm polyester mesh. The boreholes were then filled with gravel up to 0.5 m depth followed by granulated bentonite clay in order to prevent short-cut flow of water along the pipe wall. Finally, a 110-mm PVC pipe with a cap was installed around each pipe to prevent contamination. In each pipe a 10-mm PET suction pipe was installed for sampling of groundwater by use of a vacuum pump. The groundwater level was recorded weekly during the irrigation season using a plumb bob. Samples for chemical analyses were taken biweekly during the irrigation season, but biweekly or monthly thereafter. The sampling method required the most superficial groundwater to be sampled and therefore sampling was always carried out in the 0.8-m deep pipe if possible, in order to retrieve water samples that best reflected the percolating water leaving the root zone.

The method of sampling superficial groundwater for assessing leaching has been applied in other studies (e.g. Hasselgren, 2003; Larsson et al., 2003). On structured (clayey) soils there is hardly any other useful non-destructive method to estimate leaching in a field situation. When presenting data on concentrations, water balance and leaching loads, mean values of the four observations per treatment were used, i.e. groundwater data for the two willow varieties and the two blocks were pooled.

Table 1
Data on irrigation procedure and cumulative irrigation loads in a 3-year field experiment in Upplands-Bro, central Sweden.

Year	Start of irrig.	End of irrig.	Irrigation loads (mm)			
			Control	Treatment 1	Treatment 2	Treatment 3
2005	20 July	27 Sept.	33	33	66	99
2006	1 June	21 Sept.	164	164	328	492
2007	11 May	28 Sept.	282	282	564	846

Table 2
Amounts of elements applied to the different treatments through irrigation during the three years, and the mean concentration of elements in the irrigation water, in a field experiment in Upplands-Bro, central Sweden.

		Ctrl (kg/ha)	Treat. 1 (kg/ha)	Treat. 2 (kg/ha)	Treat. 3 (kg/ha)	Mean conc. (mg/L)
NO_3–N	2005	0.00	1.02	2.01	3.02	2.26
	2006	0.56	5.98	12.0	17.9	3.25
	2007	n.a.	289	578	867	103
NH_4–N	2005	0.0	66.5	132	198	205
	2006	0.0	66.8	134	200	43.7
	2007	n.a.	140	279	419	49.8
Tot-N	2005	0.0	78.5	156	234	242
	2006	0.9	173	346	519	106
	2007	n.a.	720	1440	2160	257
Chloride	2005	0.0	354	703	1060	1090
	2006	29.5	2180	4360	6540	1320
	2007	n.a.	2870	5740	8600	1020
TOC	2005	0.0	160	317	477	565
	2006	6.4[a]	607[a]	1210[a]	1820[a]	370[a]
	2007	n.a.	n.a.	n.a.	n.a.	n.a.
Tot-P	2005	0.00	0.49	0.96	1.45	1.49
	2006	0.00	7.44	14.9	22.3	4.83
	2007	n.a.	5.44	10.9	16.3	1.94

n.a.: not analysed.
[a] Only one sample analysed during the irrigation season.

2.3.2. Water balance, drainage and transport of elements to groundwater

The water balance for each treatment was calculated using a model developed for SRWC. This model applies a known relationship between actual evapotranspiration from irrigated plantations (Persson and Lindroth, 1994) and Penman evaporation, which is a function of temperature, relative humidity and radiation balance. The ratio between actual evapotranspiration and Penman evaporation (usually referred to as the crop coefficient) increases more or less linearly from around 0.5 at the beginning of the growing season to around 2 at the end. By use of linear regression with day number on the x-axis, daily values of the crop coefficient (cc) can be calculated as:

$$cc = 0.5 + 1.4*(dnum - dnum_{\rm start})/(dnum_{\rm end} - dnum_{\rm start}), \qquad (1)$$

where $dnum$ denotes day number (1 January = 1), $dnum_{\rm start}$ denotes day number at the start of the growing season, and $dnum_{\rm end}$ denotes day number at the end of the growing season.

The evapotranspiration (Evapo) was calculated as:

$$\text{Evapo} = Penman*(0.34*cc + 0.66*cc*G_{\rm rel}) \qquad (2)$$

where $Penman$ is the Penman evaporation calculated and reported by the Swedish National Meteorological Service (SMHI), cc is the calculated crop coefficient, and $G_{\rm rel}$ is the relative growth in each treatment (see below). Transpiration from plants is directly correlated with growth (Lindroth and Båth, 1999), and 56–69% of total evaporation from vegetated soil is due to transpiration (Persson, 1995). The evapotranspiration and crop coefficient estimations were based on data from four years (Persson and Lindroth, 1994). In our model the transpiration part of the evapotranspiration (set to 66%) was adjusted by a factor calculated as the ratio between estimated growth in each treatment and growth in the experimental plantation reported by Persson and Lindroth (1994).

The daily water balance was calculated according to:

$$(\text{precipitation} + \text{irrigation}) - \text{Evapo} \qquad (3)$$

Groundwater recharge was assumed to occur if the cumulative balance was positive and exceeded the previous highest value for the season. The soil water content was assumed to be equal to field capacity on 1 May each year, corresponding to a water balance of zero. This way of calculating the water balance and groundwater recharge involves a number of simplifications, including the absence of substantial preferential flow. No groundwater recharge was assumed to occur when the soil was frozen but was delayed until snowmelt, e.g. in early April 2006. The winter 2006/2007 was unusually mild and the soil was not frozen.

The daily transport of different elements down to groundwater was calculated by multiplying the groundwater recharge by the measured concentration of each element in sampled superficial groundwater. The concentration of one element was assumed to be valid until the next sampling occasion, i.e. no linear interpolation of element concentration was made for the transport calculations. Water balance, groundwater recharge and transport of elements to groundwater were calculated for the period 1 May–30 April each year. The relative retention of the different elements was calculated as the difference between load and leaching divided by the load.

2.3.3. Chemical analyses

During 2005, frequent samples of the irrigation water were taken manually, whereas during 2006 and 2007 flow-proportional samples were taken. Chemical analyses were carried out on all these samples according to Swedish standard protocols.

2.3.4. Growth and stress indicators

All measurements of plant indices were made in a central 10 times 10 m^2 net plot, i.e. 5 double rows of 10 m length. In each double row one sampling plant was systematically selected at the start of the study in 2005 and marked for repeated measurements of leaf length and shoot height. Every second week during the irrigation season, the height of the sampling plants was measured in order to keep track of the current height increment. In addition, the length of three fully developed and undamaged leaves approximately 0.4 m from the top of the tallest shoot on each sampling plant was measured. The average relative leaf length of each sampling plant was then calculated by dividing the measured leaf length by the average leaf length for all plants per willow variety on each sampling occasion. The seasonal mean leaf length for 2006 was also calculated. The height measurements were somewhat hampered by frequent browsing by deer during 2005, after which the field was fenced. Correlation between the mean leaf length and maximum shoot height and plant dry weight, respectively was analysed using linear regression with MINITAB software (MINITAB 15, Minitab Inc.).

Non-destructive biomass estimations were performed after each growing season. The shoot diameters at a fixed height (i.e. 0.8 or 1.0 m) of all shoots of the five permanent sampling plants and of another five randomly chosen plants in each net plot were measured using a calliper. For each willow variety, a set of 25 shoots was then harvested in order to determine the allometric relationship between shoot diameter and shoot dry weight according to:

$$\text{Shoot dry weight} = a^{*}\text{diameter}^{b} \tag{4}$$

where a and b are parameters obtained through non-linear regression using SIGMA Plot software (SIGMA Plot 10.0, Systat Software Inc.). The shoot dry weight of each sampled plant was calculated using this equation. For each net plot the mean plant weight was calculated and by multiplying this value by the number of live plants in the net plot, the total shoot dry weight of each plot was calculated. The effect of treatment, variety and block was tested using balanced ANOVA with MINITAB.

During summer 2006 an inventory of leaf damage caused by leaf beetles (*Phratora* spp.) was conducted. The degree of leaf damage on the permanent sampling plants in each net plot was estimated in 20% classes. Differences between varieties were tested using one-way ANOVA with MINITAB. Correlation between leaf damages and plant growth was tested using linear regression with MINITAB.

3. Results

3.1. Growth

During the first growing season (2005), plant growth corresponded to 1.2–1.8 t dry matter (DM) per hectare (Fig. 3). No significant differences were found between block, variety or treatment (results not shown). During 2006, plant growth was rapid but highly variable (2.4–17.1 t DM/ha yr) in the different blocks. Growth of the variety *Gudrun* (10.2 t DM/ha yr) was somewhat higher than that of *Tora* (9.4 t DM/ha yr), but the difference was not statistically significant. The degree of leaf damage caused by leaf beetles was significantly ($p = 0.011$; adj. $R^2 = 0.33$) and negatively correlated with growth in 2006 (results not shown), with significantly ($p = 0.006$) more damage to *Tora* (mean damage score 27%) compared with *Gudrun* (mean damage score 8%).

The poor growth for *Tora* in 2006 was mainly due to very poor growth in one of the plots with treatment 1 in the NW corner of the experimental field. During 2006, growth in that plot was estimated at 2.4 t DM/ha and the plot had a high leaf beetle damage score of 38%. However, other plots had even higher leaf beetle damage scores but higher growth.

During 2007, growth was higher than in the previous year (Fig. 3), with 12.5 and 12.6 t DM/ha yr for *Gudrun* and *Tora*, respectively. The highest growth was recorded for the control treatment in *Tora*, which had an average growth of more than 16 t DM/ha yr. No obvious insect damage was observed in 2007, and no inventory of insect damage was made.

Plant survival was generally very good, 98% for *Gudrun* and 95% for *Tora* in October 2006. No correlation was found between plant survival and plot growth (not shown). Furthermore, plot growth was not significantly correlated with treatment or variety (not shown). Only block had a significant impact on growth in year 2007 ($p = 0.022$).

The allometric equations describing the relationship between shoot diameter and shoot dry weight as established through non-linear regressions showed very good fit (i.e. adjusted $R^2 > 0.96$) except for variety *Gudrun* at the first sampling occasion (with adjusted $R^2 = 0.85$).

3.2. Stress indices

Regression analysis showed a highly significant correlation ($p < 0.000$) for variety *Tora* between relative leaf length (both measured on 26 June 2006 and the mean for the whole season, i.e. 15 sampling occasions), and individual plant growth of the sampling plants (both maximum shoot height and plant growth; Figs. 4 and 5). For variety *Gudrun* no significant correlation was found.

3.3. Groundwater

3.3.1. Groundwater level and estimated groundwater recharge

Groundwater levels varied considerably during the trial period, with clear peaks following intensive rain (e.g. in July 2006 and June

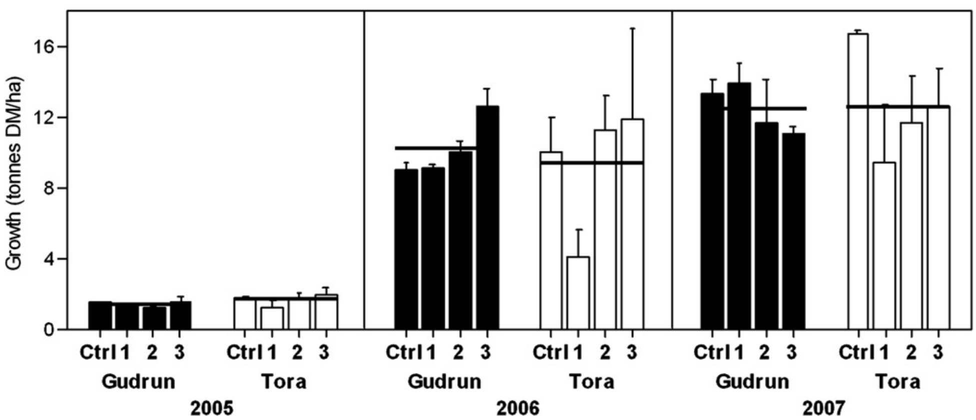

Fig. 3. Annual shoot growth 2005–2007 (t DM/ha yr) of two willow varieties used in a 3-year field experiment in Upplands-Bro, central Sweden, with error bars indicating one SE. Reference lines indicate treatment means.

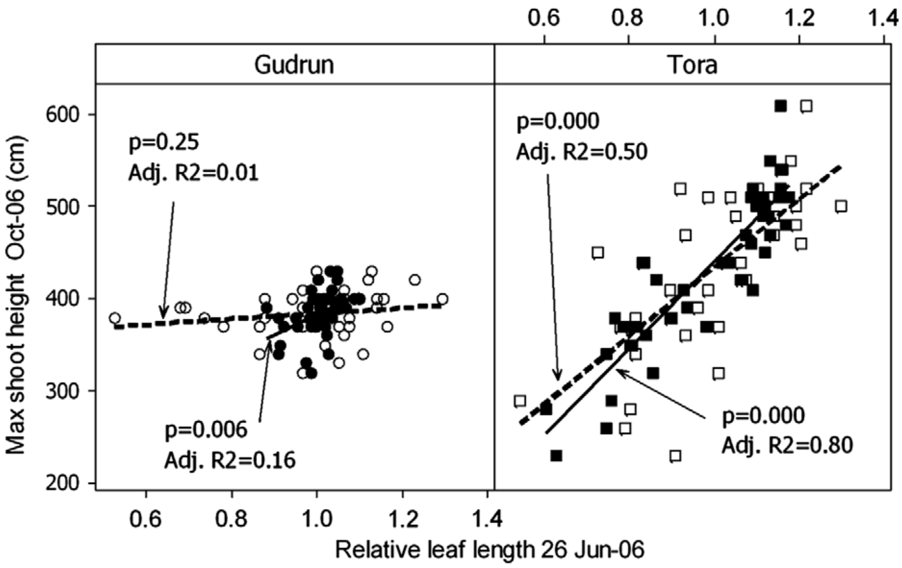

Fig. 4. Correlation between relative leaf length on 26 June 2006 (open bars/squares and dotted regression line) or mean relative leaf length for the whole season 2006 (black circles/squares and solid regression lines) and height of the tallest shoot of the sampling plants (in cm) on 5 October 2006, i.e. at the end of the second growing season in a 3-year field experiment in Upplands-Bro, central Sweden.

and September 2007) and snowmelt in April 2006 (Fig. 6). During July–August 2006 and 2007, the differences in groundwater level between the control and treatment 3 were at a maximum. The cumulative water balance for treatment 1 was higher than that for the control treatment during all three years. Furthermore, the groundwater level in control plots was typically lower than that in treatment 1.

3.3.2. Concentration of elements in groundwater and transport of elements to groundwater

The concentrations of the different compounds in the superficial groundwater are presented in Fig. 7. In groundwater total nitrogen was dominated by nitrate, and the pattern of variation in concentrations of those two parameters was similar, with concentrations increasing markedly during each irrigation season to maximum concentrations of around 100 mg NO_3–N/L during summer 2007. During intensive snowmelt in spring 2006, elevated nitrogen concentrations were found in the groundwater as well. No significant differences were present among the treatments, but the control treatment had much lower concentrations and was slowly decreasing over time. Ammonium–nitrogen occurred in high concentrations in groundwater during the irrigation seasons with the highest concentrations found in treatment 3, with peaks at around 30 mg NH_4–N/L in summer 2006.

The total phosphorus concentrations in the groundwater were below 1 mg/L for all treatments in 2005 and before irrigation started in 2006 (Fig. 7). A rapid increase in total phosphorus occurred in treatments 1–3, with peaks of more than 5 mg Tot-P/L

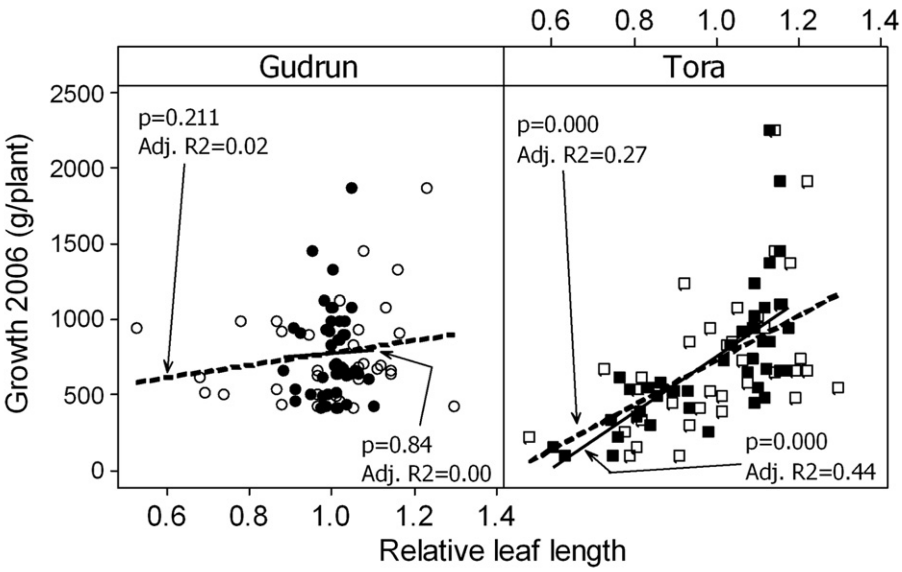

Fig. 5. Correlation between relative leaf length on 26 June 2006 (open bars/squares and dotted regression line) or mean relative leaf length for the whole season 2006 (black circles/squares and solid regression lines) and growth of the individual sampling plants during 2006, i.e. during the second growing season in a 3-year field experiment in Upplands-Bro, central Sweden.

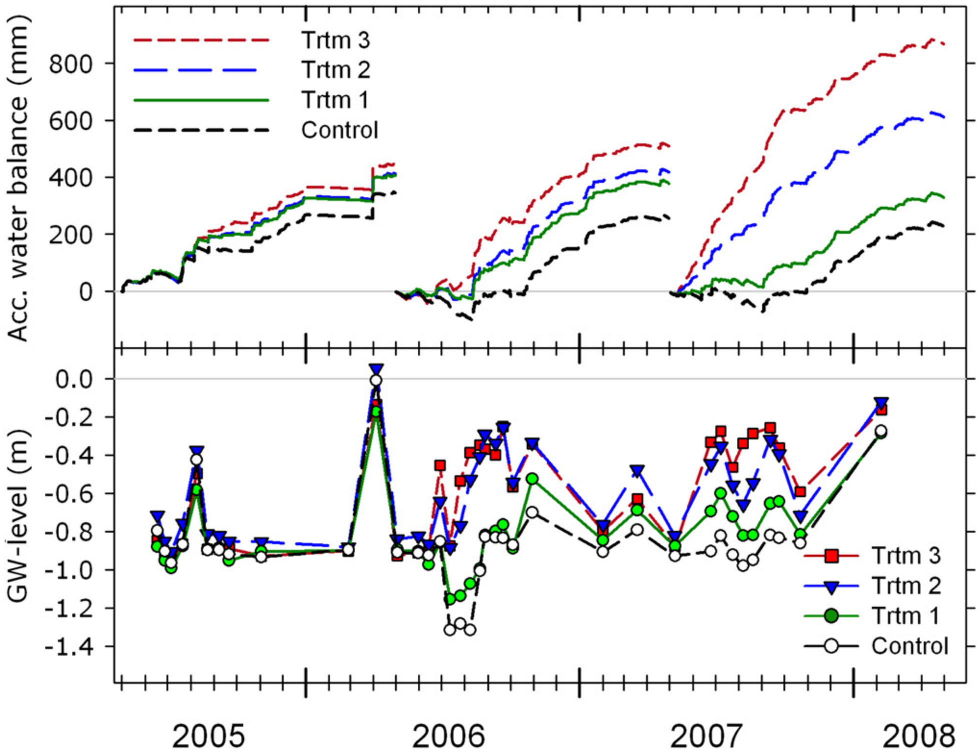

Fig. 6. Estimated cumulative water balance (top) and groundwater level in the different treatments (mean values of four observations) for a 3-year field experiment in Upplands-Bro, central Sweden.

in treatment 3. Total phosphorus concentrations decreased after the end of irrigation in 2006 and remained low for the rest of the study.

Chloride concentrations increased during the course of the study, and showed clear seasonal variation, with higher concentrations during the irrigation seasons (Fig. 7). The differences between treatments were small, but consistent with concentrations being correlated with leachate loads. Chloride concentrations were above 1000 mg Cl/L in treatments 1–3 during summer 2006 and somewhat lower during the summer of 2007. In the control treatment, a slow increase was observed in chloride concentrations over time, from close to zero at the beginning up to around 100 mg Cl/L after three years.

Concentrations of total organic carbon (TOC) in the groundwater largely followed the same pattern as chloride, but with lower concentrations of up to 300 mg TOC/L (Fig. 7). In the control treatment TOC concentrations were quite stable.

The relative retention of the different elements is presented in Table 3. Retention of total nitrogen during the first year was rather low (30–53%), but increased in 2006 to 78–85%. During 2007, retention of total nitrogen was again lower, 54–67%. For total phosphorus the relative retention was low or even negative during 2005, but during 2006 and 2007, the retention was rather high, 77–87%. The load of total organic carbon was not determined for 2007 but for 2005–2006 TOC retention was 61–72%. The retention of chloride was highest in 2005, but lower (or even negative during 2006) during the two consecutive years.

The concentrations of metals in groundwater in the different treatments are presented in Fig. 8. On the first sampling occasion, i.e. before start of irrigation, elevated metal concentrations were found in all treatments. During summer 2005 concentrations decreased, but increased again during 2006 and 2007. For most metals, except Cd, peak concentration was recorded on the last sampling occasion in May 2008. Metal concentrations were variable and not apparently related to treatment. For all metals except Cd, the concentration in the control plots also showed clear variation during the study.

Mean metal concentration in irrigation water, annual load, leaching to groundwater and relative retention for treatment 1 are shown in Table 4. For comparison, typical metal concentrations in Swedish landfill leachate and the permitted supply of metals through application of sewage sludge to arable land are also presented. Note that due to the high volume of data, corresponding leaching and retention figures for treatments 2 and 3 are not presented. Generally, the relative metal retention was low or even negative, i.e. leaching exceeded the load (except for Cr in 2006 and 2007, and Zn in 2006).

4. Discussion

The load of different elements applied through irrigation was not decided in advance. Instead, irrigation loads were based on expected precipitation deficit. The reasons for not basing irrigation on e.g. load of nitrogen were the highly variable nitrogen concentration in the leachate and the ongoing efforts by the landfill operator to introduce an efficient nitrogen treatment facility. This treatment was not successful during the course of the study and indeed in the last year, nitrogen doses were extremely high, over 2000 kg N/ha yr in treatment 3. The long-term vitality and survival of plants receiving such loads of nitrogen and other elements remain to be determined. However, no acute and severe toxicity resulted from the high loads in this study.

Growth during the first year was relatively high (1.3–1.5 t DM/ha) for all treatments compared with other newly planted SRWC fields in Sweden with first year's growth typically amounting to a few hundred kg/ha (e.g. Nordh, 2005). Plant establishment was very successful, probably due to good soil conditions, efficient weeding and suitable climate conditions. Leachate application did

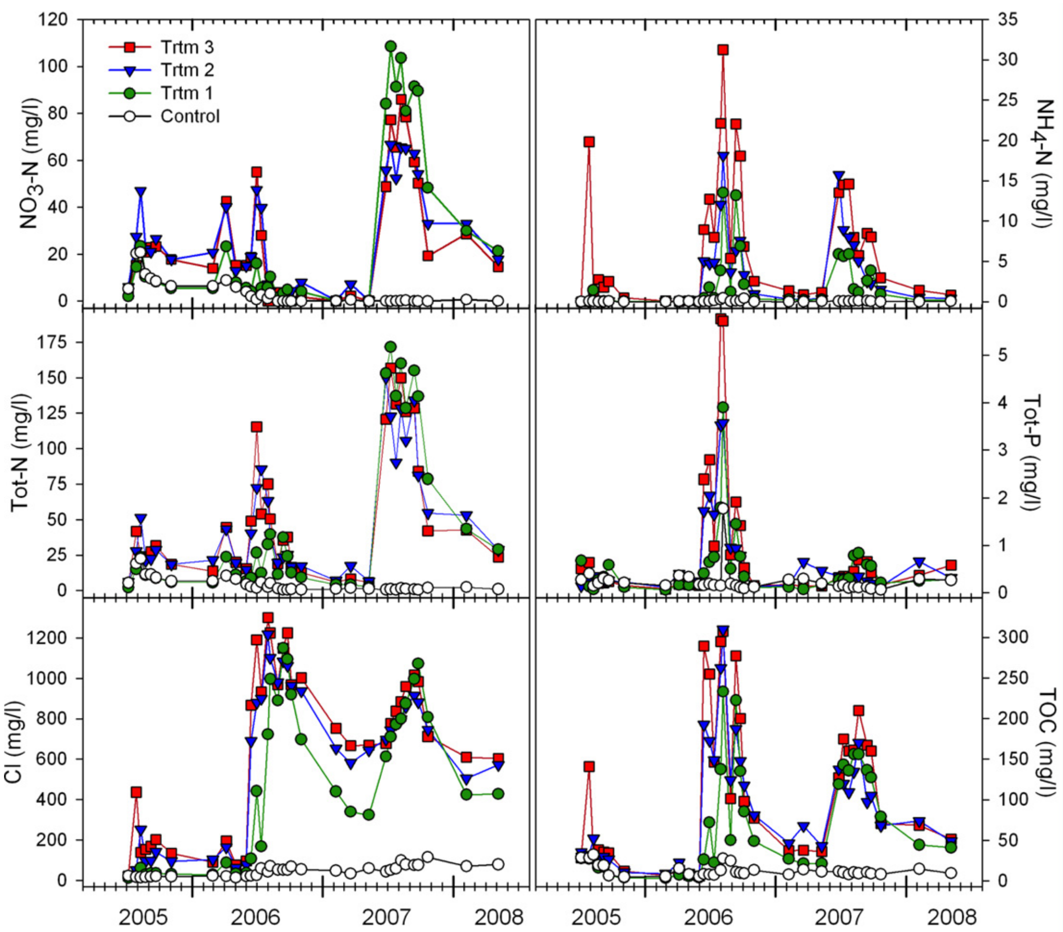

Fig. 7. Concentrations of different elements (except metals) in superficial groundwater in treatments 1–3 and the control (mean values of four observations). The first measurement in 2005 refers to sampling before start of irrigation in a 3-year field experiment in Upplands-Bro, central Sweden.

not negatively affect the plants since the net effect of application of water, plant nutrients, salts and all other elements in the leachate was close to zero. The lower growth of treatment 1 in 2006 for *Tora* was most likely due to the location of one plot in a part of the field (the NW corner) with different soil properties as indicated by soil resistivity measurements (Dahlin & Aronsson, unpublished data), combined with substantial insect damage. However, growth in treatment 1 during 2007 for *Tora* revived considerably compared with 2006.

Table 3
Relative retention (calculated as the difference between irrigation load and the leaching load divided by the irrigation load) of total nitrogen (Tot-N), total phosphorus (Tot-P), total organic carbon (TOC) and chloride (Cl) in the soil–plant system of treatments 1–3 in a field experiment in Upplands-Bro, central Sweden.

		Treat. 1 (%)	Treat. 2 (%)	Treat. 3 (%)
Tot-N	2005	39	30	53
	2006	81	85	78
	2007	67	54	58
Tot-P	2005	−102	−17	11
	2006	87	86	83
	2007	81	77	77
TOC	2005	61	67	65
	2006	72	70	71
	2007	n.a.	n.a.	n.a.
Cl	2005	54	38	26
	2006	−7.8	20	26
	2007	35	25	21

n.a.: not analysed.

In commercial Swedish willow plantations, annual growth rates of 10 t DM/ha yr or more are rare (Mola-Yudego and Aronsson, 2008). Since growth was at least as high in the tapwater-irrigated control plots, the large doses of plant nutrients added through leachate irrigation did not outweigh the potential negative effects from salt, heavy metals and other unknown elements present in landfill leachate.

Growth differences between the two varieties were not significant. Willow varieties are known to react differently to irrigation, fertilisation and landfill leachate application (Weih and Nordh, 2002; Dimitriou et al., 2003) but predictions about variety performance for a single field situation, especially applying such extreme treatments as in our study, are difficult. Before-hand, we had expected variety *Tora* to respond more rapidly to irrigation and grow much better than clone *Gudrun*, which is known to be more frost-tolerant and which we believed would be able to initiate winter dormancy early enough to avoid frost damage, despite receiving massive loads of plant nutrients in unbalanced proportions. We could not detect any substantial frost damage to plants of either *Tora* or *Gudrun* during the course of the 3-year study, despite the commonly reported risks associated with high overloads of nitrogen.

The differences between varieties also extended to leaf shape, with *Tora* having quite narrow leaves, whereas *Gudrun* has much

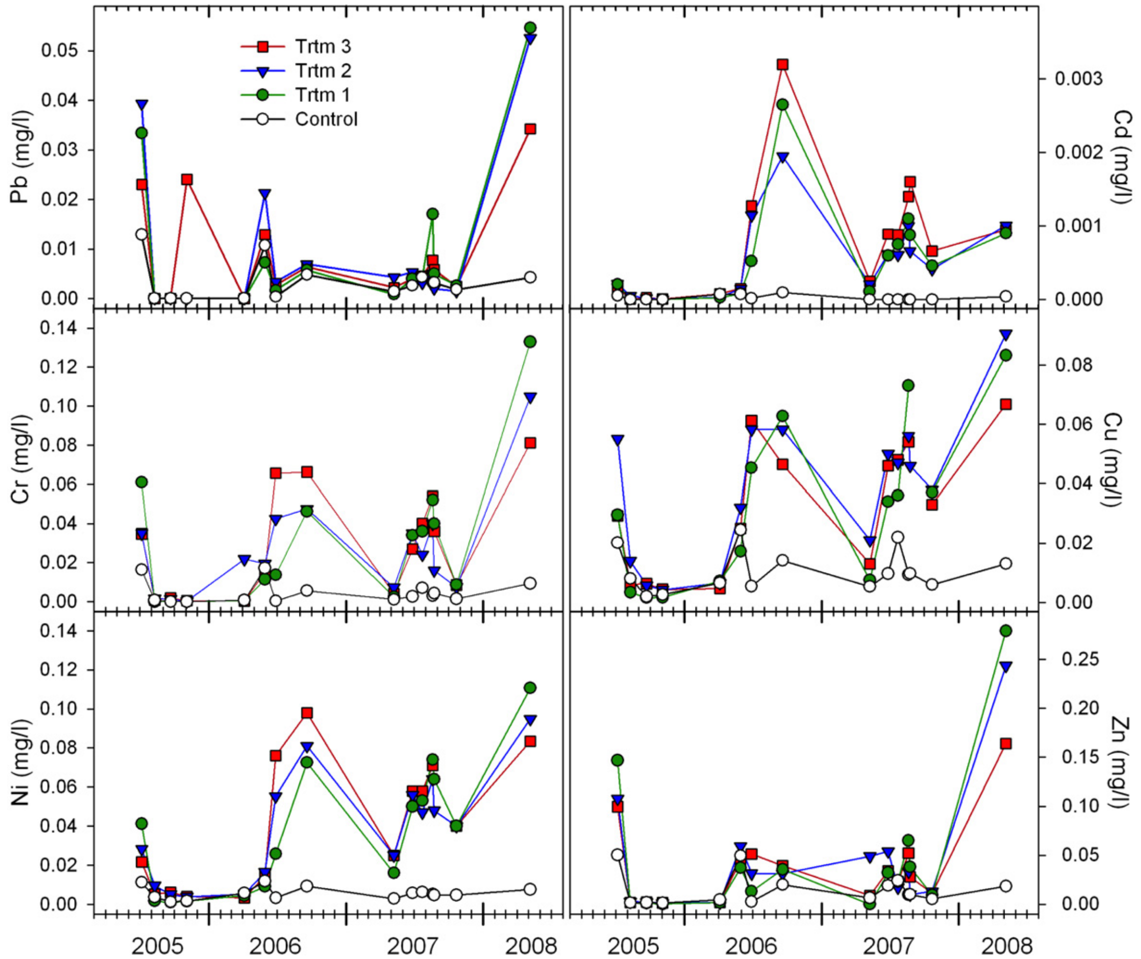

Fig. 8. Concentration of heavy metals in superficial groundwater in treatments 1–3 and the control (mean values of four observations). The first measurement in 2005 refers to sampling before start of irrigation in a 3-year field experiment in Upplands-Bro, central Sweden.

Table 4
Irrigation water concentration, irrigation load, leaching and relative retention of metals in treatment 1. Inset values + are mean concentrations in Swedish landfill leachate reported by Öman et al. (2000), while values ++ are the amounts of heavy metals permitted to be applied annually with sewage sludge to arable soils (Swedish Board of Agriculture, 2008).

		Mean conc. (μg/L)	Supply (g/ha)	Leaching (g/ha)	Rel. retention (%)
Cd	2005	$0.14^{+0.3}$	$0^{++0.75}$	0.20	n.a.
	2006	4.79	6.8	9.57	−41
	2007	0.22	0.6	2.17	−259
Cr	2005	77.3^{+17}	25.2^{++40}	46.8	−86
	2006	140	225	168	25
	2007	89.0	249	142	43
Cu	2005	16.6^{+22}	5.1^{++300}	39.2	−670
	2006	55	87.8	230	−162
	2007	23.9	66.8	173	−158
Ni	2005	80.3^{+30}	26.5^{++25}	41	−54
	2006	124	201	265	−32
	2007	71.4	200	201	−1
Pb	2005	$6.93^{+4.9}$	2.1^{++25}	25.1	−1090
	2006	6.43	10.2	21.4	−110
	2007	6.55	18.3	50.9	−177
Zn	2005	82.3^{+63}	26.3^{++600}	115	−338
	2006	126	200	131	35
	2007	85.7	240	247	−3

n.a.: not applicable.

broader leaves. This could be an explanation for the lack of correlation between leaf length and shoot growth of *Gudrun* (both height and total shoot biomass, Figs. 4 and 5). Shoots of *Gudrun* tend to be much more branched than shoots of *Tora*, making the correlation between shoot length and shoot dry weight weaker. For *Tora* relative leaf length seems to be a useful and simple indicator of stress, as previously suggested by Dimitriou et al. (2006). However, this involves the use of control plants with low levels of stress for comparison.

The calculations of water balance for the different treatments were based on a rather simplistic approach, namely Penman evaporation adjusted by a crop coefficient varying over time. Errors in this model were expected, especially during unusually hot, windy and/or rainy days. However, there seems to be a good correlation between model output of the cumulative water balance and measured groundwater levels (Fig. 6), both as regards the variation over time and the differences between treatments. This indicates that the model can produce reasonable daily estimates of water balance. The only data available for validation of the model were calculated retention of chloride (Table 3), since chloride is practically inert and thus should not be retained in the soil–plant system. However, some chloride is taken up by plants, and initially there is probably a build-up of soil salinity, delaying and reducing the chloride leaching. However, there was positive chloride retention for each treatment except treatment 1 during 2006. This indicated that drainage (and leaching) was underestimated, which could be due to overestimation of evapotranspiration by the model.

Although growth was not severely affected by leachate irrigation, groundwater quality was affected by leaching of nitrogen and other elements, including metals (Figs. 7 and 8). Nitrogen concentrations in the groundwater were much higher than in groundwater sampled in Danish SRWC fertilised with inorganic fertilisers (Mortensen et al., 1998), or in intensively irrigated and fertilised Swedish SRWC (Aronsson, 2000; Larsson et al., 2003). Godley et al. (2005) found maximum NO_3–N concentrations in porewater from an SRWC field irrigated with landfill leachate to be approximately 45 mg/L, even though less nitrogen was applied compared with our treatment 1. The high nitrogen concentrations in groundwater in our study, especially during the third year, and the high leaching loads expressed as low relative retention (Table 3) indicate massive overloading of the system. The supply of nitrogen in 2007 was equal to 720, 1440 and 2160 kg N/ha for treatment 1, 2 and 3, respectively. For comparison, fertilisation recommendations for SRWC in Sweden developed by Ledin et al. (1994) suggest annual rates of around 80–100 kg N/ha yr. Moreover, the elevated NH_4–N concentrations in the groundwater were higher than after a very intensive wastewater irrigation of willows grown in lysimeters (Dimitriou and Aronsson, 2004). All the above indicate that the total nitrogen supply with irrigation should probably be considerably lower than that in treatments 2 and 3. High losses of nitrogen in Sweden are a problem due to the risks for eutrophication of the Baltic Sea and other waters, but in the short-term perspective leaching losses of NH_4–N is a greater problem since they can cause acute toxicity in surrounding water courses receiving drainage water from the site. This calls for either reduced loads or improved nitrification of the landfill leachate before use for irrigation.

Nitrogen retention was low during the first year of crop establishment but this was expected and supports the widely accepted opinion that SRWC should not be fertilised or irrigated with nutrient-rich residues in the year of establishment due to the poorly developed root system (Aronsson, 2000; Dimitriou, 2005; Gustafsson et al., 2007). Nitrogen retention was highest for all treatments in 2006 and was around 80% even for the relatively high nitrogen supply (equal to 346 and 519 kg/ha for treatment 2 and 3, respectively). In 2007, there was a considerable decrease in nitrogen retention in all treatments. Although 80% nitrogen retention in SRWC is not as high as values reported in other related literature for wastewater treatment in SRWC fields (Larsson et al., 2003), it is similar to results from landfill leachate irrigation in SRWC in southern Sweden (Hasselgren, 2003) and can be considered rather satisfactory under the circumstances (high N supply). In any case, it is interesting to speculate about the expected nitrogen leaching in SRWC, especially when nitrogen-rich water is available in large amounts and high nitrogen loads are used. The loads of nitrogen through irrigation during the third year of this study were unexpectedly high, and negatively affected the usefulness of the results obtained. However, since the plants did not apparently react negatively to the loads, we were able to use the results obtained for making a regression analysis of nitrogen leaching as a function of nitrogen load. Linear regression using annual nitrogen loads during year 2 and 3 as predictor gave the equation:

$$\text{N-leaching} = 0.446 \times \text{N-load} - 46.4$$

with an adjusted R^2 of 0.97. This equation is valid for this site only, but gives a hint about plants being very important in managing nitrogen.

Low phosphorus concentrations in landfill leachate have been identified as potentially responsible for lower growth when used for irrigation of willows (Alker, 1999; Dimitriou et al., 2006; Hasselgren, 2003), and therefore minimal phosphorus leaching can be expected after leachate irrigation. However, phosphorus retention was below 90% for all treatments and years (Table 3) and therefore not entirely satisfactory compared with results from similar studies (Hasselgren, 2003; Jonsson et al., 2006). In our experiment, phosphorus concentrations in groundwater were particularly high during the irrigation season 2006, with the highest concentrations in treatment 3, which had a peak of more than 5 mg Tot-P/L (Fig. 7). This coincided with a peak of around 2 mg Tot-P/L in the control treatment, indicating some kind of experimental or sampling error partly explaining the high concentrations found. However, clearly elevated phosphorus concentrations in groundwater followed leachate irrigation, despite the relatively modest phosphorus loads of 7.4–22.3 kg/ha. The irrigation water concentration of Tot-P was almost three times higher during 2006 than in the two other years (Table 2) for some unknown reason. The extensive phosphorus leaching during 2006 contradicts our previous finding that a phosphorus supply to SRCW that somewhat exceeds the amounts taken up by the crop (i.e. theoretically 8–10 kg P/ha yr; Dimitriou, 2005) should not be hazardous to the groundwater. However, if phosphorus concentrations in landfill leachate are close to the average concentrations in Swedish landfill leachate according to Öman et al. (2000), i.e. in the order of 1.3 mg P/L, then the risks due to phosphorus are expected to be small.

Better leachate quality than that during 2006 seems to be an essential for sustainable leachate application, not only in terms of phosphorus but also in terms of most heavy metals present in the leachate. During 2006, concentrations of all metals except for Pb were significantly higher in the landfill leachate than those in 2005 and 2007 (Table 4), and were in general substantially higher than the respective mean Swedish values (Öman et al., 2000). This led to high loads for the SRWC, even in treatment 1, where the amounts of Cd, Cr and Ni supplied in 2006 and 2007 were well above the permitted metal loads referred to as upper limits for application of sewage sludge to arable land (see Table 4). This increases the risk of accumulation of heavy metals in the soil. Alker et al. (2003) and Godley et al. (2005) suggest that there is no accumulation of metals in the upper 0–25 cm soil after leachate irrigation of SRWC when metal loads are within reasonable limits, and therefore risks of heavy metal accumulation are small. In our experiment, no soil analyses were conducted in terms of metal concentrations and thus the degree of metal accumulation in soil due to leachate irrigation could not be examined. However, since the relative retention of most metals was negative, no accumulation is expected to have occurred. Metal leaching to surrounding water courses is not environmentally preferable to soil accumulation, and in the long run the loads of heavy metals need to be reduced considerably in order to achieve system sustainability.

The method of groundwater sampling for leaching estimates in field plots seems appropriate. The concentration of the practically inert chloride in control plots showed a small increase over time (Fig. 7). This indicates small cross-contamination between plots, as was also indicated by soil resistivity measurements carried out in the same field and presented by Dahlin and Aronsson (submitted for publication). However, such cross-contamination was of minor importance over the three years of very intensive application of landfill leachate.

5. Conclusions

The conclusions derived from this field study were as follows:

Above-ground plant growth was not significantly affected by irrigation with landfill leachate compared with no irrigation (year 1) or irrigation with tapwater (years 2–3). There were also no significant differences between the two willow varieties tested. Leaf length can be used as a rapid stress-indicator for the variety *Tora*, since it was significantly correlated with shoot growth. The same did not apply for the variety *Gudrun*. The concentrations of different elements in groundwater increased as a result of irrigation with landfill leachate, clearly reflecting the varying irrigation water concentrations and loads over time. Absolute retention of nitrogen, phosphorus and heavy metals was not satisfactory, but in case of nitrogen and heavy metals understandable, given the massive loads. Phosphorus behaved unexpectedly, with low retention despite moderate loads. Relative retention of total nitrogen was found to be more or less linear, even at loads exceeding 2000 kg Tot-N/ha. Improved pre-treatment of the leachate before use in irrigation is required to ensure a more sustainable treatment system.

Acknowledgements

This experiment was financially supported by Ragnsells Avfallsbehandling AB, which is gratefully acknowledged. Richard Childs and Lars-Erik Berggren are also gratefully acknowledged for technical assistance provided during the study.

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