



Purification function of Short Rotation Willow Coppice

1. Introduction

Short Rotation Willow Coppice (SRWC) is a perennial crop (lifetime : 20-25 years) of woody species planted at very high density (> 15,000 stools/ha) intended for energy wood production. The term "Short Rotation" is derived from the frequency of harvesting: every 2-3 years. The biomass produced is a renewable energy source which may, for example, be used as a substitute for fuel oil for heating. Every hectare of SRWC burnt saves approximately 3500-4500 litres of fuel oil per year.

The first experiments with SRWC were conducted in Sweden in response to the oil crisis of the 1970s. These experiments were part of an intensive policy of developing renewable energies and aimed to replace fossil energy with new energy sources. Extensive research into the plant biology and production systems of different fast-growing species (*Alnus*, *Betulus*, *Populus*, *Salix*) concluded that intensively cultivated willow gave the best performance in terms of productivity (DIMITRIOU, 2005). Later, SRWC was used to treat waste waters and for phytoremediation of polluted soils (heavy metals).

In Sweden, perennial high yields of woody biomass quickly led to the need of fertilisation. Sewage sludge spreading and fertigation by pre-treated wastewater was then introduced for economic (compared with conventional mineral fertiliser) and environmental (use of waste) reasons. Sewage sludge spreading and wastewater fertigation gave yields that were 2 to 3 times higher than in crops with no inputs (LABRECQUE & TEODORESCU, 2001; ADEGBIDI *et al.*, 2001).

Currently, SRWC covers 16,000 ha of land in Sweden and systematically combines biomass production with the use of different types of effluent. Sweden's Enköping wastewater treatment plant is most often used as an example. At Enköping, 75 ha of SRWC are fertigated by sludge runoff water and produce approximately 9 t(DM)/ha/year.

In Europe other countries, such as Denmark, the UK, Belgium, Finland, Estonia and now France have also developed SRWC crops with the emphasis on its purification function.

In western France the objective of the Wilwater programme, begun in September 2004, was to demonstrate the benefits of SRWC for the use of sewage sludge or pre-treated wastewater on 100 ha of SRWC over three years. This summary presents the results of the trials established under the Wilwater programme at a dozen sites chosen for the diversity of the inputs that could be used.

2. SRWC as a vegetation filter : the concept

The shallow rooting behaviour of willow, combined with a high planting density, makes SRWC suitable for use as a vegetation filter. Around 80% of the root hairs of willow are found at depths of less than 40cm (RYTTER & HANSSON, 1996; CROW & HOUSTON, 2004). The high planting density (> 15,000 stools/ha) allows the development of a dense root hair system over the entire area occupied by the crop. Many scientists have applied the concept of a vegetation filter to SRWC, in particular for the treatment of organic compounds and the absorption of directly assimilable nutrients and some heavy metals (PERTTU & KOWALIK, 1997; ARONSSON, 2001).

On all the sites studied under the Wilwater programme, the willows were planted in double rows. The two rows in a double row were spaced 75cm apart and the double rows were spaced 1.5 m apart. For waste water fertigation, a drip irrigation system was buried between the double rows on alternate double rows.

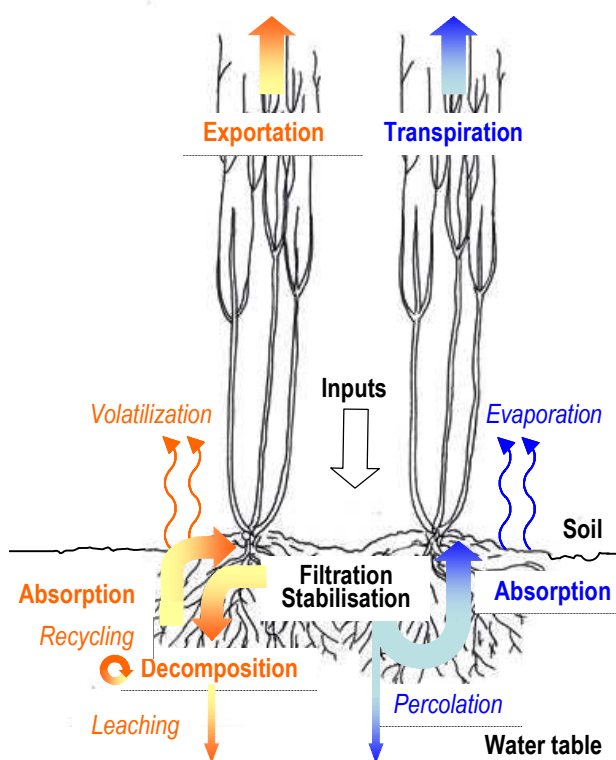


Figure 1 : Water and nutrient cycles in a SRWC

The soil-willow system is more than just a vegetation filter ; it may be regarded as a “biological reactor” (JOSSART *et al.*, 1999). This reactor is the location of many ecological processes, the most important of which are:

- Stabilisation and retention of suspended matter and other nutrients in the effluent by the soil particles via constant exchanges with the soil solution.
- Decomposition of organic matter by the soil fauna (macro- and micro-organisms, bacteria, fungi).
- Absorption, by the willow roots, of nutrients (supplied in directly assimilable form by the effluent or produced by organic matter decomposition) and water supplied by the effluent.

In summary, the soil fauna breaks down the effluents applied to the crop, the soil particles control the availability of nutrients to the willow and the willow absorbs some or all of the nutrients supplied by the effluent (depending on the level applied).

Willow offers a number of advantages when grown in coppice under fertigation or fertilisation by sewage sludge. The main advantages are:

- A long growing season¹ and therefore a long season for extracting nutrients from the soil.
- A perennial root system which restricts winter leaching of nitrogen (ARONSSON, 2001).
- High evapotranspiration² (MARTIN & STEPHENS, 2006) and a root system which tolerates slight, long-term anoxia (JACKSON & ATTWOOD, 1996) which together allow high daily rates of irrigation.
- The ability to resort to luxury consumption of some minerals, including nitrogen (ADEGBIDI *et al.*, 2001; KLANGWESTIN & PERTTU, 2002; WEIH & NORDTH, 2002).
- The option of planting on non-rotational fallow land and the long life provide a long-term outlet for the application of sewage sludge.
- Sewage sludge may be applied to SRWC when it cannot be applied to conventional crops (summer).
- A non-food crop, which reduces the risk of the human food chain being contaminated with undesirable substances from the effluents applied to the SRWC (heavy metals).

¹ Normally defined by external temperatures higher than 5°C.

² Higher than the PENMAN reference ETP (PERTTU, 1999) in summer: $ETP(\text{willow}) = (1.1 \text{ to } 1.8) \times ETP(\text{PENMAN})$

3. Effluents of different origins and compositions

Under the Wilwater programme, the purification potential of SRWC was investigated at around ten sites selected for the diversity of the potential inputs. Different effluents were applied to the SRWC :

- Waste water from industrial sources: landfill leachate (site 1), wastewater from a fish processing factory (site 2) and wastewater from a knacker's yard (site 3).
- Domestic waste water, fertigated on SRWC for secondary treatment (site 4) and tertiary treatment (site 5).
- Water from agricultural sources: pre-treated pig slurry (biological treatment, site 6)
- Liquid sewage sludge (site 7 to 10).

Industrial effluents (sites no.1, no.2 and no.3) and agricultural ones (site no.6) are characterised by a phosphorus imbalance (excess) and a potassium imbalance (high excess) which put them outside the optimum macronutrient ratio (N/P/K = 100/14/72) normally recommended in the input (PERTTU & KOWALIK, 1997). An excess of potassium in the soil ($K_2O/MgO > 3$) could lead to a magnesium deficiency in the willow. Industrial effluents also have a high SAR³. Irrigation with water at SAR > 10 is not advisable (HALLETT *et al.*, 2002). The application of excess sodium could cause soil destructuration. Industrial effluents have a COD/BOD₅ ratio which indicates the presence of organic matter which is difficult to biodegrade (DCO/DBO₅ >3). Judging from the few parameters measured, domestic effluents from small collectivities (sites no.4 and no.5) are particularly well balanced.

Table 1 : Composition of fertigated waste water at sites under the Wilwater

Site	Inputs m ³ /ha	pH	COD mg(O ₂)/L	BOD ₅ mg(O ₂)/L	COD/BOD ₅	Total Kjeldahl nitrogen mg/L	Nitrate mg/L	Phosphorus mg/L	Potassium mg/L	N/P/K	Calcium mg/L	Magnesium mg/L	Sodium mg/L	SAR
no.1	668	8.0	670	6	112	47	68	6	530	100/10/840	52	37	507	13
no.2	4315	8,5	152	29	5	12	14	7	46	100/36/242	29	8	128	5
no.3	1526	8,6	75	5	15	5	11	2	42	100/18/476	36	5	630	26
no.4	884	7,6	556	300	2	91		16		100/12				
no.5	1331	7,5	57	41	1	40	2	7		100/12				
no.6	1628					239	< 1	87	1922	100/37/804				

Sewage sludge is characterised by a phosphorus imbalance (excess) and a potassium imbalance (high excess) which puts it outside the optimum macronutrient ratio (N/P/K = 100/14/72) normally recommended for inputs (PERTTU & KOWALIK, 1997). This imbalance means that the application plan will be restricted by the phosphorus level; it cannot be based on nitrogen alone. Furthermore, when compared with wastewater fertigation, application of sludge for biomass production presents disadvantages associated with the lack of water in the sludge applied.

Table 2 : Composition of sewage sludge applied at sites under the Wilwater programme

Site	Inputs t(DM)/ha	pH	Dry matter %	Total Kjeldahl nitrogen mg/L	Phosphorus g/kg(DM)	Potassium g/kg(DM)	N/P/K	Calcium g/kg(DM)	Magnesium g/kg(DM)
no.7	1,7	12,5	2,8	80	39	4	100/48/4	347	5
no.8	2,5		2,5	83	51	8	100/61/10		
no.9	11,8	7,3	5,4	71	27	8	100/39/11	37	3
no.10	1,8	7,4	4,5	96	30	13	100/31/14	32	6

³ Sodium Adsorption Rate = $\frac{[Na^+]}{\sqrt{([Ca^{2+}] + [Mg^{2+}])}}$ where [Na⁺], [Ca²⁺] et [Mg²⁺] are in mmol.L⁻¹

4. The main lessons to be learned from the Wilwater programme

4.1. Yield estimates

Yield estimates, obtained in August 2007, predict average annual yields of 8.4 t(DM)/ha/year for the six fertigated sites, 5.3 t(DM)/ha/year for the four sites receiving sewage sludge, and 7.2 t(DM)/ha/year for the two sites with no inputs. Note that the annual yield at the end of the first growing season is estimated to be less than 1.5 t(DM)/ha for most sites. At site 12 (no inputs), annual coppice yield more than doubled between the first and second harvests (3.6 t(DM)/ha/year compared with 8.8 t(DM)/ha/year). The low yield obtained at the first harvest was attributed to poor management of the companion vegetation (adventitious weeds) during the willow's first growing season.

Estimated yields in August 2007 (sites 1, 3, 4, 5, 6, 7, 9, 10 and 11) and some yields measured at harvest (sites 2, 8 and 12) were lower than the theoretical yields of 8-10 t(DM)/ha/year in the case of SRWC fertilised with sludges and of 10-12 t(DM)/ha/year in the case of fertigated SRWC. Two main reasons have been proposed: (1) the growing season had not finished when yields were estimated, in August 2007, and (2) the actual yields were measured over the first two harvesting cycles whereas yields increase at the third harvest then stabilise for subsequent ones.

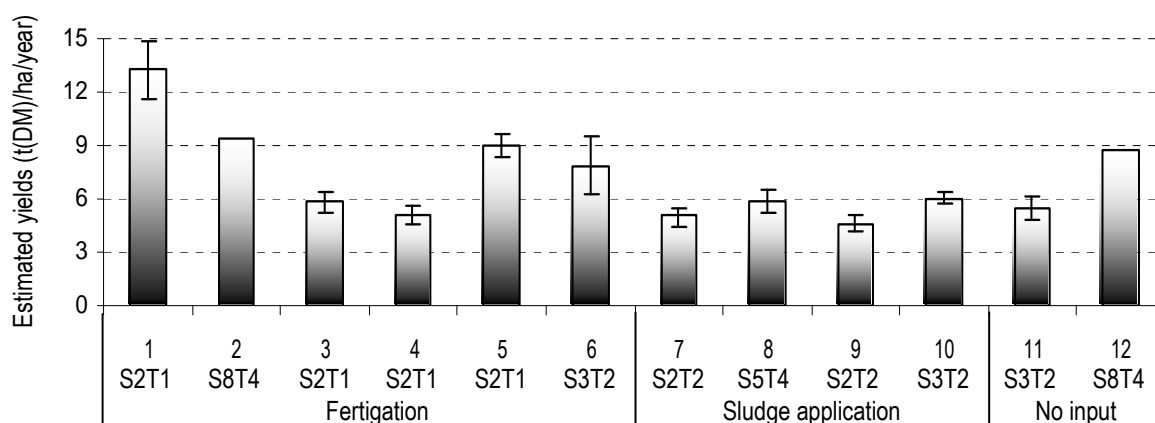


Figure 2 : Estimated yields as a function of type of effluent applied (August 2007) (Averages \pm standard errors, n = 18 to 36) – (site 1: landfill leachate, site 2: agri-food waste water, site 3: knacker's yard waste water, site 4: domestic waste water (secondary treatment), site 5: domestic wastewater (tertiary treatment), site 6: pig slurry, sites 7-10: sewage sludge, sites 11 and 12: no input) – (“SxTy” refers to the age of the stools (S) (x years) and the stems (T) (y year) at the time of the yield estimate or harvest) – (On every sites, four willow clones have been planted (Björn, Olof, Tora, Torhild). The clonal effect on yields is not taken in account)

4.1.1. Waste water fertigation

At the sites fertigated by waste water, the estimated average yield (8.4 t(DM)/ha/year) was low due to the large variation between sites. At sites 3 and 5, the low yield estimates are probably due primarily to the heterogeneous soil conditions at the plot and poorly controlled competition between the willow and companion vegetation during the willow's first growing season. Over the six fertigated sites, yields of 12 t(DM)/ha/year are expected from the second harvest, except at sites 4 and 1. At site 4, the willows planted in irrigated double rows did not start to regrow at the end of the first winter. At site 1, it is hoped that the estimated yield of over 16 t(DM)/ha/year on one of the two plots at the site will continue for future harvests.

In general, a significant difference in yield was observed between the irrigated and non-irrigated double rows, except at the sites fertigated by domestic waste water.

- On the sites fertigated by industrial effluent (except for fertigation by landfill leachate) and pig slurry, the **non-irrigated double rows performed better**. Note that in the crop fertigated by pig slurry, the willows planted in irrigated double rows probably did not survive due to the massive nitrite input caused by a malfunction at the biological pre-treatment plant. Application of nitrite in the field may cause serious burning of the vegetation (VAN DEN HENDE, 1950).

- At the site fertigated by landfill leachate, the **irrigated double rows performed better** with an estimated yield 2-3 times higher than that of non-irrigated double rows.

4.1.2. Application of sewage sludge

For sites fertilised with sewage sludge, the estimated yields are low and relatively uniform. On these sites, very little water is supplied with the sewage sludge and the expected yield from the second harvest onwards is only 8 t(DM)/ha/year. At site 8, the low yield obtained after the first harvest (5.8 t(DM)/ha/year) was attributed to the age of the willows (4 years) at the time of harvest. Beyond three years, the annual biomass yield tends to decline (BULLARD *et al.*, 2002).

4.2. Chemical composition of the woody biomass

The dry matter (DM) content of the fertigated willow stems was significantly lower than that of the willow stems fertilised by application of sewage sludge or receiving no inputs. Use of water by the willow is therefore less efficient in the case of waste water fertigation; this observation is confirmed by a number of international publications (WEIH & NORDTH, 2002). Among other significant differences, the nitrogen and potassium levels in fertigated willow stems are significantly higher than the nitrogen and potassium levels in willow stems fertilised by application of sewage sludge or receiving no inputs. This highlights the luxury consumption capacity, particularly for nitrogen. By contrast, luxury consumption of phosphorus was not observed. No difference in levels of these elements between willow stems fertilised by sewage sludge and those receiving no input has been validated statistically.

The mean macronutrient ratio in the harvestable biomass, calculated for all the fertigated sites, is N/P/K = 100/15/78. The K in this ratio varies greatly but no trend by type of waste water was observed. This ratio is closest to the theoretical optimum ratio N/P/K = 100/14/72. For the sites fertilised by sewage sludge or not fertilised, the macronutrient ratios in the harvestable biomass are close at N/P/K = 100/14/47 (sludge deficient in potassium) and N/P/K = 100/15/42. The low potassium level in these ratios is due to a deficiency of this element in the sludge and the rapid decline of its availability in the soil.

Table 3 : Chemical composition of woody biomass as a function of type of effluent applied (Lower limit mean upper limit)

		Fertigation	Land application	No input	References *
Dry matter	%	31 38 48	39 44 49	36 42 50	
Nitrogen	g.kg(DM) ⁻¹	3.9 6.3 8.6	4.6 5.8 7.5	4.1 5.6 8.5	3.3-8.2
Phosphorus	g.kg(DM) ⁻¹	0.5 0.9 1.2	0.6 0.8 1.0	0.5 0.9 1.4	0.4-1.3
Potassium	g.kg(DM) ⁻¹	2.0 4.9 7.7	1.8 2.8 4.8	0.7 2.4 4.3	1.5-4.8
Calcium	g.kg(DM) ⁻¹	1.6 2.4 3.7	1.9 3.0 5.5	2.0 3.3 5.8	3.2-7.4
Magnesium	g.kg(DM) ⁻¹	0.2 0.4 1.2	0.3 0.4 0.6	0.3 0.4 0.6	0.2-1.0
Sodium	g.kg(DM) ⁻¹	0.01 0.11 0.41	0.02 0.06 0.09	0.03 0.06 0.15	
Copper	mg.kg(DM) ⁻¹	1.8 3.4 5.0	1.0 2.6 3.8	1.6 3.2 7.2	3.7-11.6
Zinc	mg.kg(DM) ⁻¹	26.0 60.2 112.5	26.7 57.7 80.7	39.4 62.3 100.3	25.2-161
Cadmium	mg.kg(DM) ⁻¹	0.6 1.2 2.2	0.2 0.6 1.1	0.3 0.7 1.4	0.5-4.1
Nickel **	mg.kg(DM) ⁻¹	< 0.50 - 0.98	< 0.50	< 0.50	2.5-5.5
Chromium **	mg.kg(DM) ⁻¹	< 0.10 - 0.59	< 0.10 - 0.98	< 0.10	2.1-3.8
Lead **	mg.kg(DM) ⁻¹	< 0.10 - 0.52	< 0.10	< 0.10 - 0.14	0.4-1.3
Mercury	mg.kg(DM) ⁻¹	< 0.05	< 0.05	< 0.05	0.03

* extreme values taken from: ADEGBIDI *et al.* (2001), ADLER *et al.* (2005), LABRECQUE & TEODORESCU (2003), MAXTED *et al.* (2007), ADLER *et al.* (1998), LABRECQUE & TEODORESCU (1997), MAXTED *et al.* (2005), SANDER & ERICSSON (1998).

** many values are under the detection limit, mean calculation has no significance.

In most of the input methods trialled, the potential export of cadmium, zinc and sometimes lead by willow was greater than the inputs of these elements. The balances – calculated on the basis of the initial stocks of minerals in the soil, the mineral input from the effluent and the mineral export by the woody biomass – thus indicated potential exhaustion of the cadmium stock in 1-6 exploitation cycles (20-120 years). The accumulation of some metals, particularly cadmium, in the

harvestable parts of the willow is of great interest to the scientific community, specifically for phytoremediation of polluted soils (DICKINSON & PULFORD, 2005). In view of the risks to human health posed by cadmium and the high levels of cadmium found in willow wood, specific filters are required in order to collect the most volatile ashes when burning willow which had been used for the phytoremediation of polluted soils (DIMITRIOU *et al.*, 2006). However, the moderate cadmium contents in the willow wood obtained under the Wilwater programme make the installation of such filters not necessary.

4.3. Mineral export by the biomass and theoretical balance

4.3.1. Waste water fertigation

In the case of fertigation of SRWC, for an expected yield of 10-12 t(DM)/ha/year, the potential export by the willow crop would be 63-75 kg(N)/ha/year, 9-11 kg(P)/ha/year, 50-59 kg(K)/ha/year, 24-29 kg(Ca)/ha/year and 4-5 kg(Mg)/ha/year. The potential annual export of nitrogen is therefore high but barely exceeds the export levels for conventional crops.

For sites fertigated by waste waters of industrial origin, the balances – calculated on the basis of the initial stocks of minerals in the soil, the mineral input from the effluent and the mineral export by the woody biomass – demonstrated a potential doubling of the soil sodium stock in some months only – willow consumes very little sodium. The balances also confirmed :

- The excess of phosphorus and potassium in the input (potential doubling of the phosphorus stock in approximately twenty years and of the potassium stock in 1-2 years) for fertigation by pre-treated pig slurry
- The low levels of macronutrients for fertigation by waste water from knacker's yards (potential exhaustion of the nitrogen stock in 5-6 exploitation cycles and the phosphorus stock in 1-2 exploitation cycles). In the latter case, sewage sludge (which is rich in phosphorus) could be applied in each spring after harvest.

Under the Wilwater programme, exportation levels of 28-105 kg(N)/ha/year have been estimated (Table 4). These exportation levels do not reflect the whole capacity of the {soil-willow} system to treat the entire nitrogen content of the effluents. The denitrification, natural process responsible for the transformation of the nitrate into N₂, can also treat large amount of nitrate. However, the denitrification measurement requires specific equipments so that the denitrification has not been measured on any site under the Wilwater programme. Furthermore, the denitrification process is hard to manage in natural areas. Its efficiency depends on many factors : soil and climatic conditions on site, irrigation frequency and presence of the bacterian population responsible for process functioning. The scientific community believes that 200 kg(N)/ha/year could be treated by the {soil-willow} system, taking in account denitrification and long term nitrogen immobilisation in the soil.

Table 1 : Macronutrient amounts supplied by the effluent and contained in the woody biomass. (Input / Exportation)

Site	n°1	n°2	n°3	n°4	n°5	n°6	n°7	n°8	n°10
Azote	40 / 105	75 / 59	13 / 37	115 / 28	61 / 60	270 / 44	141 / 30	207 / 58	172 / 37
Phosphore	4 / 13	29 / 8	2 / 6	14 / 3	7 / 8	74 / 8	28 / 4	125 / 10	53 / 6
Potassium	335 / 76	161 / 44	64 / 33			2061 / 22	5 / 15	21 / 33	24 / 24
Calcium	33 / 45	107 / 23	55 / 13				527 / 13		57 / 16
Magnésium	24 / 6	32 / 4	8 / 2				7 / 2		11 / 4
Sodium	320 / 2	521 / 1	962 / 1						

4.3.2. Application of sewage sludge

When sewage sludge was applied, the annual mineral export by the crop was lower than for fertigation. This is explained by lower yields and generally lower mineral concentrations in the harvestable biomass. For an expected yield of 8-10 t(DM)/ha/year, the potential export by the willow crop could be 47-58 kg(N)/ha/year, 8-10 kg(P)/ha/year, 28-33 kg(K)/ha/year, 30-37 kg(Ca)/ha/year and 4-5 kg(Mg)/ha/year.

Generally, the balances calculated for the sites with land application demonstrated the problem of inputs with excess phosphorus and insufficient potassium by showing the potential doubling of the phosphorus stock in less than one

exploitation cycle and potential exhaustion of the potassium stock in 2-3 exploitation cycles. To limit over-fertilisation of phosphorus, the application of slurries at a rate of 30-40 m³/ha/year represents an acceptable level. Moreover, given that wood ash is high in potassium and calcium (PARK *et al.*, 2005), the addition of wood ash to the sludge could help to balance the potassium input. When ash is used to adjust the sludge, the associated calcium means that liming of the plot before planting willow does not appear to be necessary.

4.4. Impacts of cropping and inputs on agronomic characteristics and water quality

The aim of the programme was to demonstrate the purification capacity of SRWC so the trials took place very early and were very short (3 years) relative to the life of a SRWC. The impact of fertilising SRWC with waste water or sewage sludge on the agronomic characteristics of the plantation could not therefore be established properly. The annual input of minerals was generally less than 2% of the initial stocks. However, in the case of sludge fertilisation, the annual input of phosphorus was often around 8% of the initial stock of phosphorus in the soil. Under fertigation with industrial effluents, the annual input of sodium was greater than 100% of the initial stock of sodium in the soil.

4.4.1. Massive nitrate leaching during the first winter

At all the sites, studies of the nitrogen present before and after the winter showed that, depending on the previous crop and soil type, 60-80% (70-120 kg(N)/ha) of the soil nitrate stock was likely to be lost by leaching over the whole soil profile during the winter after planting. This huge amount of nitrate leaching during the first autumn/winter, confirmed by many scientific papers (MORTENSEN *et al.*, 1998; ARONSSON *et al.*, 2000; DIMITRIOU & ARONSSON, 2004; GOODLASS *et al.*, 2006) is due to mineralisation of the organic matter produced by tilling the soil before the crop is planted. Note that during the first growing season, the potential accumulation in the woody biomass (without any inputs) was only 10-20 kg(N)/ha. ARONSSON & BERGSTRÖM (2001) collected up to 187 kg(N)/ha, leached in the form of nitrates, when fertiliser was applied during establishment of a plantation. Therefore **no inputs** should be added during the first growing season.

4.4.2. Soil salinisation

In the irrigated double rows at the site fertigated by landfill leachate, at the peak of the irrigation season (August 2007), the ESP (Exchangeable Sodium Percentage = $[Na^+]/CEC$ where $[Na^+]$ and CEC are in meq/100g), which was initially in the normal range (1% < ESP < 2%), reached an average of 16% and up to 23% locally. In the non-irrigated double rows the ESP was unchanged from the starting levels. According to HALLETT *et al.* (2002), if the ESP exceeds 15%, irrigation must be stopped in order to permit leaching of excess sodium. C. CHEVERRY, a member of the scientific committee of the Wilwater programme, believes that there is a real risk of soil destructuration if the ESP exceeds 12% and the pH of the soil simultaneously exceeds 8. The risk of soil destructuration is therefore recognised at the site fertigated by landfill leachate. In addition to these risk, the soil fauna which is responsible for biotransformation the effluent could be disrupted by abnormally high levels of sodium in the soil.

In order to limit soil salinisation, the irrigation system must be shut down, at least during the three winter months, to allow the exchangeable cations in the soil to regain equilibrium. During the summer the soil must remain sufficiently moist to prevent any risk of over-saturating the soil with sodium. An irrigation system could be installed in all the double rows; the impact of sodium on the soil would then be halved.

For fertigation with a pre-treated pig slurry, the impact of an excessive potassium input was observed from a clear change in the K₂O/MgO ratio in the soil. This ratio, initially 1.8 (correct) reached 5.9 after just two irrigation seasons. If this ratio exceeds the threshold value of 3, the potassium input should be reduced or magnesium added in order to prevent a magnesium deficiency in the willow.

4.4.3. Impact of the inputs on water quality

At one of the fertigated sites, ion exchange membranes buried at a depth of 60cm provided observations of nitrate leaching immediately below the irrigated double rows at the peak of the irrigation season (August 2007). This leaching was encouraged by high rainfall during the summer 2007. Studies of the hydrological balances showed summer water percolation at nearly all the sites. The irrigation rate was therefore superfluous to effective precipitation. Control of the irrigation rate should therefore take account of the meteorological conditions, particularly rainfall.

Except for the site fertigated by pre-treated pig slurry, no increase in the nitrate content of the groundwater was observed. The lack of variation cannot be interpreted as a lack of impact. It indicates that the amount of nitrate reaching the groundwater would be largely diluted by the overall volume of the groundwater and serves as a reminder that the chemical signature of the groundwater is the result of the overall practices employed on the catchment area.

5. Recommendations

With regard to the soil type and the fertiliser application plan for willow coppice, yields of 8-10 t(DM)/ha/year and 10-12 t(DM)/ha/year are possible for application of sewage sludge and fertigation, respectively. Fertiliser application plans can be based on these theoretical yields. If the denitrification potential of the site is known, the fertiliser application plan can take this new term in account.

When planning irrigation with pre-treated effluents, the calculation of the amount of water to apply must consider:

- The infiltration capacity of the soil and the presence of groundwater close to the surface
- Local rainfall and potential evapotranspiration
- The nitrogen and phosphorus input
- The salt inputs ((Na⁺ et K⁺). Excessive salt input may have a serious impact at the agronomic level. In the case of an initial ESP lower than 2%, a sodium input (kg/ha) lower than 10 times the initial soil Na₂O content (mg/kg) seems to cause a relatively low risk of soil salinisation. Monitoring of the soil sodium content is however required.


When planning fertilisation with sewage sludge, the levels applied should be based on phosphorus in order to limit over-fertilisation of this mineral. In Sweden, legislation restricts phosphorus inputs to 50 kg(P₂O₅)/ha/year if the assimilable phosphorus (P-AL) content of the soil is greater than 92 mg(P₂O₅)/kg(DM) or 80 kg(P₂O₅)/ha/year otherwise. Despite the absence of legislation in France, it is proposed, on the basis of maximum annual potential export of phosphorus by the crop, to limit the phosphorus input to :


- 25 kg(P₂O₅)/ha/year if the assimilable phosphorus content of the soil (Olsen) is greater than 140 mg(P₂O₅)/kg(DM)
- 75 kg(P₂O₅)/ha/year if the assimilable phosphorus content of the soil is lower than 80 mg(P₂O₅)/kg(DM) .
- 50 kg(P₂O₅)/ha/year otherwise.


The height of the willows in the second year of growth means that applications cannot be made every year. Given that 60-70% of the nitrogen and phosphorus in slurries is available to the crop in the year following application, it should be possible to apply :

- 1.4 times the annual amount exported by the biomass after harvest. Several weeks or months are required for the nutrients of the effluents to be available. With the aim to avoid nitrate leaching during winter, sludge spreading should be done at the beginning of the growing season.
- an amount equal to the annual export by the biomass at the start of the second year of growth.
- none in the third year.

6. Conclusions

 Under the Wilwater programme, the study of the purification effects of SRWC followed the first three years in the life of a SRWC which would remain in place for around twenty years. The outlook for long-term development of the different plantations is therefore based on theoretical balances. Moreover, the trials concentrated on the ability of SRWC to absorb and retain the elements provided by the effluent rather than its purification function in the strict sense of the term. Validation of this function would have required experiments under controlled conditions, i.e. with a large amount of specific equipment in the plantations.

 Nevertheless, the trials demonstrated the real advantages of SRWC in terms of consumption of the nutrients supplied by different effluents. SRWC is of particular interest for collective tertiary treatment of effluents from small settlements (domestic effluents for less than 500 inhabitant equivalents) or industries. Industrial effluents must not have an imbalance. Too high a sodium concentration, for example, is a serious contra-indication. In all cases, an irrigation method allowing better distribution of the effluent over the plot would increase the effectiveness of the treatment.

 For sewage sludge application the advantages of SRWC are less clear-cut. The need to avoid excessive phosphorus enrichment of the soil means that the quantity applied cannot be increased above the application level for conventional crops. Furthermore, inadequate water input with sludge application appears to restrict development of the plantation. Nevertheless, application of sewage sludge to SRWC remains an attractive solution in specific cases: for example, if the municipality wishes to guarantee an outlet for its sludge at times when it could not be applied to conventional crops (summer) or when the municipal land application plan includes many crops intended for human consumption (market garden crops).

In conclusion, the Wilwater programme has made it possible to demonstrate that SRWC is an attractive solution for the tertiary treatment of balanced municipal or industrial effluents and to determine the inputs which are compatible with sustainable development of the crop. Sludge application to SRWC should be reserved for very specific cases. The results of field trials conducted over three years and the balances and forecasts derived from them will need to be confirmed by long-term studies.

References

- ADEGBIDI H.G., VOLK T.A., WHITE E.H., ABRAHAMSON L.P., BRIGGS R.D. & BICKELHAUPT D.H., 2001. Biomass and nutrient removal by willow clones in experimental bioenergy plantations in New York State. *Biomass and Bioenergy* 20, pp. 399-411
- ADLER A., VERWIJST T. & ARONSSON P., 2005. Estimation and relevance of bark proportion in a willow stand. *Biomass and Bioenergy* 29, pp. 102-113
- ARONSSON P.G., 2001. Dynamics of nitrate leaching and ¹⁵N turnover in intensively fertilized and irrigated basket willow grown in lysimeters. *Biomass and Bioenergy* 21, pp.143-154
- ARONSSON P.G. & BERGSTRÖM L.F., 2001. Nitrate leaching from lysimeter-grown short-rotation willow coppice in relation to N-application, irrigation and soil type. *Biomass and Bioenergy* 21, pp. 155-164
- ARONSSON P.G., BERGSTRÖM L.F. & ELOWSON S.N.E., 2000. Long-term influence of intensively cultured short-rotation Willow Coppice on nitrogen concentrations in groundwater. *Journal of Environmental Management* 58, pp. 135-145
- BULLARD M.J., MUTILL S.J., Mc MILLAN S.D., NIXON P.M.I., CARVER P. & BRITT C.P., 2002. Yield improvements through modification of planting density and harvest frequency in short rotation coppice *Salix* spp. – I : Yield response in two morphologically diverse varieties. *Biomass and Bioenergy* 22, pp. 15-25
- CROW P. & HOUSTON T.J., 2004. The influence of soil and coppice cycle on rooting habit of short rotation poplar and willow coppice. *Biomass and Bioenergy* 26, pp. 497-505
- DICKINSON N.M. & PULFORD I.D., 2005. Cadmium phytoextraction using short-rotation coppice *Salix* : the evidence trail. *Environment International* 31, pp. 609-613
- DIMITRIOU I., 2005. Performance and Sustainability of Short-Rotation Energy Crops Treated with Municipal and Industrial Residues. Doctoral thesis, Swedish University of Agricultural Sciences, 38 pages
- DIMITRIOU I. & ARONSSON P., 2004. Nitrogen leaching from short-rotation willow coppice after intensive irrigation with wastewater. *Biomass and Bioenergy* 26, pp. 433-441
- DIMITRIOU I., ARONSSON P. & WEIH M., 2006. Stress tolerance of five willow clones after irrigation with different amounts of landfill leachate. *Bioresource Technology* 97, pp. 150-157
- GOODLASS G., GREEN M., HILTON B. & McDONOUGH S., 2006. Nitrate leaching from short-rotation coppice. *Soil and Use Management*, doi : 10.1111/j.1475-2743.200600080.x, On Line, 7 pages
- HALLETT J., ALKER G., GODLEY A. R., 2002. Landfill leachate management using short rotation coppice – Operational guide. WRc Report number CO5127, 62 pages
- JACKSON M.B. & ATTWOOD P.A., 1996. Roots of willow (*Salix viminalis* L.) show marked tolerance to oxygen shortage in flooded soils and in solution culture. *Plant and Soil* 187 (1), pp. 37-4
- JOSSART J.M., GOOR F., NERINCKX X., LEDENT J.F., 1999. Le taillis à très courte rotation, une alternative agricole. Seconde édition. Université Catholique de Louvain, Laboratoire d'Ecologie des Grandes Cultures
- KLANG-WESTIN E. & PERTTU K., 2002. Effects of nutrient supply and soil cadmium concentration on cadmium removal by willow. *Biomass and Bioenergy* 23, pp. 415-426
- LABRECQUE M. & TEODORESCU T.I., 2001. Influence of plantation site and wastewater sludge fertilisation on the performance and foliar nutrient status of two willow species grown under SRIC in southern Quebec (Canada). *Forest ecology and management* 150, pp. 223-239
- LABRECQUE M. & TEODORESCU T.I., 2003. High biomass yield achieved by *Salix* clones in SRIC following two 3-year coppice rotations on abandoned farmland in southern Quebec, Canada. *Biomass and Bioenergy* 25, pp. 135-146
- MARTIN P.J. & STEPHENS W., 2006. Willow growth in response to nutrients and moisture on a clay landfill cap soil – II : Water use. *Bioresource Technology* 97, pp. 449-458
- MAXTED A.P., BLACK C.R., WEST H.M., CROUT N.M.J., McGRATH S.P. & YOUNG S.D., 2007. Phytoextraction of cadmium and zinc by *Salix* from soil historically amended with sewage sludge. *Plant and Soil* 290, pp. 157-172
- MORTENSEN J., NIELSEN K.H. & JØRGENSEN U., 1998. Nitrate leaching during establishment of willow (*Salix viminalis*) on two soil types and at two fertilization levels. *Biomass and Bioenergy* 15 (6), pp. 457-466
- NISSEN L.R. & LEPP N.W., 1997. Baseline concentrations of copper and zinc in shoot tissues of a range of *Salix* species. *Biomass and Bioenergy* 12(2), pp.115-120.
- PARK B.B., YANAI R.D., SAHM J.M., LEE D.K. & ABRAHAMSON L.P., 2005. Wood ash effects on plant and soil in a willow bioenergy plantation. *Biomass and Bioenergy* 28, pp. 355-365
- PERTTU K.L., 1999. Environmental and hygienic aspects of willow coppice in Sweden. *Biomass and Bioenergy* 16 (1), pp. 1-6. In LABRECQUE M. & TEODORESCU T.I., 2003. High biomass yield achieved by *Salix* clones in SRIC following two 3-year coppice rotations on abandoned farmland in southern Quebec, Canada. *Biomass and Bioenergy* 25, pp. 135-146.
- PERTTU K.L. & KOWALIK P.J., 1997. *Salix* vegetation filters for purification of waters and soils. *Biomass and Bioenergy* 12 (1), pp. 9-19
- RYTTER R.-M. & HANSSON A.-C., 1996. Seasonal amount, growth and depth distribution of fine roots in an irrigated and fertilized *Salix viminalis* L. plantation. *Biomass and Bioenergy* (11), pp 129-137
- SANDER M.-L. & ERICSSON T, 1998. Vertical distributions of plant nutrients and heavy metals in *Salix viminalis* stems and their implications for sampling. *Biomass and Bioenergy* 14(1), pp. 57-66
- VAN DEN HENDE A., 1950. Des effets de l'épandage de nitrites sur des cultures en plein champ. *Plant and Soil* 2(2), pp. 223-230
- WEIH M. & N.-E. NORDTH, 2002. Characterising willows for biomass and phytoremediation : growth, nitrogen and water use of 14 willow clones under different irrigation and fertilisation regimes. *Biomass and Bioenergy* 23, pp. 397-413