Willow vegetation filters: Principles, results and economy

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Abstract

During recent years, it has become obvious that it is both environmentally and economically appropriate to use vegetation filters of different short rotation willows (*Salix spp.*) to purify waters and soils. Swedish experiences of vegetation filter efficiencies have been demonstrated in several laboratory, field lysimeter and full-scale experiments. However, there are still many questions to be answered, for example, how the uptake and allocation mechanisms of heavy metals and recalcitrant organic constituents function, or which maximum doses are possible in a particular situation without any risk of leachate losses. As far as plant nutrition is concerned, the past two decades of integrated research in Sweden have demonstrated that the willows have capacity for efficient uptake both of macro and micro nutrients, which is reflected in their high productivity.

The purpose of this paper is to present some results on how vegetation filter stands of willow, irrigated with municipal wastewater, can function as purification plants, while at the same time producing fuel wood. This twofold utilisation benefits both the environment (e.g. less air pollution from wood compared with fossil fuels) and the economy (combined wastewater treatment and fuel wood production).

Treatment plants for wastewater purification using various types of vegetation filters have been tried both in Sweden. The experiences consider both the nutrient and heavy metal uptake, and the whole process chain from establishment, cultivation and harvesting of the wastewater irrigated willows stands to the utilisation of the wood in heating plants.

Key words: ***Economy, Sludge, Vegetation filter, Wastewater treatment, Willow.***

Introduction

The Swedish energy forestry research started already in the mid-1970s, as an immidiate consequence of the energy crisis in the world. However, the Swedish import of fossil fuels (mainly mineral oil) was very high, and the import made us too dependent on the policy in other countries. Investigations into domestic, renewable wood fuels, principally willows (*Salix* spp.) have, therefore, been performed for more than twenty years now (Sirén 1980, Perttu 1987, 1989, Christersson *et al.* 1993). In the beginning of the 1980s, the agriculture of the western world had reached such dimensions that the overproduction of various agricultural products started to be a serious problem. It was, therefore, rather natural to shift the introduction of short rotation forestry (mainly willows) from marginal land, such as peat bogs, abandoned farm land, etc., to more productive agricultural soils. At the end of the decade, there was also an interest in finding ways to take care of domestic wastewaters in a more natural way, combined with use of its potential as a nutrient carrier (Perttu 1992, Aronsson and Perttu 1994). Successively, this has led to research programmes on willows for multipurpose use (Christersson and Sennerby-Forsse 1994).

Investigations concerning the effect of nutrient and heavy metal uptake by willows on the purification of municipal wastewaters and sludges have been performed during the last eight to ten years, in the Northern and Western Europe (e.g. Hasselgren 1988, Perttu

1992, Kutera and Soroko 1994, Obarska-Pempkowiak 1994, Hodson *et al*, 1994, Nielsen 1994). Also in Estonia, experiments using such filters have started recently in cooperation with Sweden (Kirt 1994, Koppel 1994, Kuusemets and Mauring this issue).

Willows have shown to possess valuable properties with respect to wastewater treatment. Except for a high biomass production, when treated properly what concerns establishment and management, they also are efficient in taking up nutrients (Ericsson 1981), have a high evapotranspiration rate (Persson and Lindroth 1994), and show a clone specific capacity of taking up heavy metals (Yazdani 1992, Landberg and Greger 1994).

Efficient and inexpensive wastewater treatment systems are needed in many countries, and willow vegetation filters may possibly meet such needs. They seem to have the capacity to purify wastewaters and at the same time be producers of biomass for energy purposes.

The aim of this paper is to shortly present some of the results achieved so far on vegetation filter research and to encourage the use of this type of filter systems. Furthermore, the paper also contains information in order to minimise problems associated with handling and deposition of wastes which, otherwise, could be a significant environental risk if not correctly managed.

Material and methods

Vegetation filter applications

Wastewater experiments

Municipal wastewaters consist normally of a solution with nutrients in well-balanced proportions looked upon from a green plant's point of view (Perttu 1993). The proportions by weight of the three main macro nutrients in wastewater (with nitrogen set to 100 and with the optimal proportions given within brackets) are the following: i) nitrogen (N) = 100 (100), ii) phosphorus (P) = 18 (14), and iii) potassium (K) = 64 (72), (Ericsson 1981). This shows that municipal wastewaters in most cases, when industrial wastewaters are not mixed in, are almost ideal nutrient solutions for growing willows.

There are a few systems in practical use in Sweden, where wastewaters are applied for irrigation of willow coppice and agricultural crops (Aronsson and Perttu 1994). The willow is effective in this matter because of many reasons (cf. Perttu and Kowalik 1996): i) its shoot length and stem diameter growth take place during the whole growing season (Nilsson and Eckersten 1983), ii) its good ability to take up nutrients is manifested in many cultivations without any tendency to leakage (Christersson et al. 1993, Christersson and Sennerby-Forsse 1994), iii) and its high evapotranspiration rate which well exceeds the Penman potential evaporation (Lindroth and Halldin 1988). Also from an ethic point of view, being neither a food nor a fodder crop, this makes willow an attractive filter crop for wastewater treatment. From an economic viewpoint, use of willow filters are less costly than construction of and running traditional treatment plants (Rosenqvist *et al.* 1996).

As an example of investigations on willow forests, irrigated with wastewater, the results from a pilot trial performed at Bogesund, north of Stockholm, during 1992-1994 are presented shortly. The stand is a mixture of many willow clones as a result of a genetic crossing programme. These clones were planted about 13 years ago but were for about 10 years left without any treatment what so ever because of reduced research fundings. When the pilot study was started, the mixed stand had been neither fertilised nor harvested (fertilising normally takes place every year and harvest every fourth year in this type of cultivation), which means that it showed a typical shortage of nutrients and, as a result of that, a low production. The stand was coppiced in March 1992 before the experiment started, and the estimated yield was in average less than 500 kg dry matter per hectare and year. The area was divided into four plots (each 20 x 15 m^2 in size), two for wastewater irrigation (A, B) and two for control (C, D) (cf. Table 1). According to the soil characterisation made just after coppice, the plots A and C, situated in the upper part of a gentle slope, showed a relative shallow soil profile with considerably drier conditions compared to the plots C and D, further down on the slope. Between the upper and the lower plots there was earlier saved a 20-year old spruce stand which now could be used as a barrier. A barrier was also created between the two upper and the two lower plots, respectively, by saving a 10 m untreated willow strip between them. Three times every year during the growing seasons, domestic wastewater (i.e. wastewater from one-family households after simple sedimentation) was distributed on plots A and B, thus resulting in the following approximate annual inputs on a hectare basis: 250 kg N, 25 kg P, 90 kg K, 35 kg Ca, 5 kg Mn, and about 100 mm of water.

The experiment shows clearly that there is a marked effect on the willow growth when the stands were irrigated with municipal wastewater, in this time supplied only three times per year. The biomass yield during the first two years was 2-3 times higher in the fertilised plots compared to the unfertilised plots (Table A1). The terms "dry" and "wet" in the table refers to the soil profile giving somewhat drier and wetter conditions, respectively, when compared with each other.

Table 1. Relative comparison of willow growth between plots, fertilised with municipal wastewater (A, B), and control plots (C, D) during 1992 and 1993. The stools were randomly selected..

Variable	Fertilised plots 1992 / 1993		Unfertilised plots 1992 / 1993	
	A ("dry")	B ("wet")	C ("dry")	D ("wet")
No. of stools investigated	60 / 60	60 / 60	60 / 60	60 / 60
Nitrogen supply, kg ha^{-1}	264 / 250	228 / 250	0 / 0	0 / 0
Ave. no. of shoots $stool^{-1}$	5.3 / 4.7	6.4 / 7.1	5.2 / 5.1	5.5 / 5.0
Average height, cm	136 / 205	174 / 274	102 / 141	130 / 170
Average diameter, mm	6.3 / 10.2	7.5 / 12.1	4.3 / 5.9	5.5 / 7.4
Ave. prod., g DM $stool^{-1}$	16.3 / 57.7	24.6 / 95.5	5.9 / 17.1	13.3 / 34.1
Prod. increase 1993, %	100 / 254	100 / 288	100 / 190	100 / 156
Ave. prod. (A+B/C+D), %	213 / 299		100 / 100	

When comparing the 3-year yields of the different plots after the final harvest, we can find some interesting results from the growing seasons of 1992-1994 with regard to the effect of both water and of nutrients. Two out of the three main months of the growing seasons (June-August) had lower precipitation than normal (i.e. 30-year mean value 1961-1990), and the calculated Penman potential evapotranspiration (ET) was 2-3 times higher than the precipitation. The monthly average temperatures were higher during two of the three years. The climate and yield data are summarised in Table 2, and it is now possible to estimate the effect of the drought between the "dry" and "wet" plots and of the effect of the wastewater irrigation, respectively. The drought effect, given by the yield ratio between the "dry" and "wet" plots (according to A/B and C/D, respectively), was in the range of 51-58 %, thus implying that the drier plots had just above half of the production compared to the wetter plots, (independent of fertilisation). The effect of the wastewater irrigation (a combined nutrient and water effect) can similarly be estimated using the ratios A/C and B/D, respectively. In this case the effect of wastewater gave an increase in the yield by 164-185 %. This implies that the nutrients and the additional 100 mm of water in the wastewater solution almost doubled the yield.

Table 2. Climate data for June-August, 1992-1994 and the 3-year total stem biomass yield in the different plots (from the wastewater experiment north of Stockholm).

Variable / patch	1992	1993	1994	Normal values (1961-1990)	Yield ($tDM\ ha^{-1}$)
Precipitation, mm	165	219	142	178	
Potential ET, mm	430	430	430	430	
Air temperature, °C	16.8	13.9	17.6	15.8	
A, "dry", irrigated					18
B, "wet", irrigated					35
C, "dry", untreated					11
D, "wet", untreated					19

<u>Wastewate economy</u>

According to Rosenqvist *et al.* (1996), it is economically realistic to use willow vegetation filters for treatment of wastewater from small and medium size municipalities compared with conventional technical treatment. This is summarised in Table 3 below, including also the two cases: a) a Summer alternative without storage of the wastewater produced during the Winter, meaning that this wastewater is treated in an existing plant (with low N removal), and b) a Winter alternative according to which the wastewater during the cold season (assumed to be 6 months) is stored in a pond. For more details concerning the prerequisites, etc., see the publication by Rosenqvist *et al.* (1996).

Table 3. Average costs for different treatment cases (after Rosenqvist *et al.* 1996).

Case	Treatment system	Average costs (SEK $(kgN)^{-1}$)
i)	Conventional P treatment during the whole year	40-80
ii)	Conventional P and N treatment during the whole year	70-180
iii)	Soil-plant system during the Summer (6 months) and a conventional P treatment during Wintertime	55-95
iv)	Soil-plant system during The Summer (6 months) and a conventional P and N treatment during Wintertime	70-170
v)	Soil-plant treatment during the Summer (6 months) with wastewater storage during Wintertime	90-120

Municipal sludges

When the main part of the water is removed from municipal wastewaters, the solid material left consists of sludges. Removal of the water is done in several ways: sedimentation, biological treatment, chemical precipitation, and a combination of two or more of these methods (Perttu 1992). The sludge can be treated in several ways to improve its hygienic status before use (Morsing 1994). The most common methods in Sweden are anaerobic stabilisation and storage during a minimum of six months.

About 80 % of the nitrogen in wastewater is normally found in the water solution. Since water, by definition of sludge, is removed, the nutrient composition differs considerably from that of wastewater. Thus, the macro nutrients (N, P, and K) in a typical Swedish municipal sludge have the following proportions 100, 73, 9, i.e. sludges are unbalanced in comparison with wastewaters (Perttu 1992).

Use of sludges must also be valued against the risk of spreading heavy metals, the most important being cadmium, as well as recalcitrant organic substances, such as pesticides. If acceptable to farmers and consumers, sludge has to be classified by type, heavy metal content, hygienic standard, etc. From a green plant's point of view, municipal sludge is less suitable than wastewater as fertiliser. Still the main part of the economic calculations have been performed for sludge, because of lack of suitable data from fullscale experiments with wastewaters. However, a report on the wastewater economy is in press in an international journal (Rosenqvist *et al.* 1996), see above.

Table 4. Prerequisites for the comparison of economy using sewage sludges and commercial fertiliser, respectively (after Perttu 1994).

Variable	Sewage sludge	Commercial fertilisers
Real interest rate, %	6	6
Total rotation period, years	24	24
Production, 1st harvest after 2 years, t DM	6	-
Production, 2nd harvest after 4 years, t DM	20	-
Subsequent harvests after every 2nd year, t DM	24	-
Production, 1st harvest after 4 years, t DM	-	25
Subsequent harvests after every 4th year, t DM	-	48
Governmental establishment support, SEK	0	0
Price of wood chips delivered at a district heating plant, SEK $(t\ DM)^{-1}$	540	540
Nutrient content in sludge kgN $(t\ DM)^{-1}$	33	-
Value of sludge for the farmer, SEK	0	-
Amount of nitrogen used year 1, kg	33	0
Amount of nitrogen used year 2, kg	66	60
Amount of nitrogen used year 3, 5, 7,...23, kg	198 (99 kg yr^{-1})	120 (60 kg yr^{-1})

The main prerequisites for using sludge compared to commercial fertilisers are presented in Table 4. The costs include all types of labour (including the farmer's own work), machinery, wood chip transport, and real interest. The transport cost of sludge to farmland is set equal to that to a landfill area, although other estimations have implied that the latter would be higher than the former (Hahn 1992). The cost of spreading the sludge in the plantation is, similarly, set equal to that for commercial fertiliser. These two entries are, therefore, not separately handled either as revenues or costs.

The calculations for using municipal sludges include harvesting every second year, compared to traditional willow forestry with 4-year harvesting cycles. In spite of the much higher harvesting costs, the use of municipal sludge as fertiliser is more favourable both for the farmer and the municipality compared with commercial fertilisers. The profit for the farmers increases annually by 500-650 SEK per hectare, depending on the wood productivity at the site concerned and, similarly, the costs for the municipalities are reduced by 250-400 SEK per tDM of sludge (Table 5). The nitrogen content in sludge is typically 30-35 kg per tDM, so the average annual sludge, supplied to a willow cultivation, amounts to 2.5-3 t DM ha^{-1}, which then equals 80-100 kg of N, the doses being recommended as optimal per hectare and year in commercial cultivations. The municipal annual cost reduction on a hectare basis is consequently 625-1200 SEK. The total profit of using municipal sludge instead of commercial fertilisers would then be 1125-1850 SEK per hectare and year.

Table 5. Summary of the farmer's economy using sewage sludges and commercial fertilisers for cultivation of willow.[23]

Variable	Sewage sludges	Commercial fertilisers
Revenue per hectare and year, SEK	5775	5140
Costs (per hectare and year), SEK	4185	4175
i) Establishment	*1000*	*975*
ii) Fertilisation and management	*220*	*875*
iii) Harvesting and chipping	*1815*	*1170*
iv) Transport and administration	*1150*	*1155*
Total net	1590	965

Contaminated soils

Restoration of soils contaminated by metals or other substances is under discussion in many European countries today. There are different strategies to be applied, but the strategy is to use the capacity of some willow clones to take up heavy metals. With a suitable technique, it might be possible to remove heavy metals from contaminated soils, whereafter the willow can be used as wood fuel in heating plants with efficient cleaning of smoke gases and proper handling of ashes. In this way, the volumes of contaminations are reduced to handling of relatively small amounts of ashes rather than large amounts of soils. Recent techniques used in fullscale district heating plants has shown that removal of cadmium from ash is both efficient and relatively inexpensive (Mats Westermark, Vattenfall, pers. comm.).

It has been shown, for example, that the concentration of zink (Zn) in plant tissues (roots) can be as high as 5 % on a dry matter basis (Dickinson *et al.* 1994). Swedish field investigations on cadmium (Cd) uptake by willows have also been performed (Ericson 1994, Östman 1994). The analyses show that 21 g Cd per hectare and year can be removed by stem harvest, which should be compared with an average content of approximately 600 g Cd per hectare in Swedish arable soils (Notter 1993). This content was and still is a result of the use of commercial cadmium-contaminated phosphorus fertilisers in agriculture as well as of atmospheric deposition. In some areas in southernmost Sweden, the Cd content of wheat grains sometimes exceeds the limits for human consumption. To grow willow in these areas during one or two rotation periods seems to be a promising way of reducing the cadmium content of the soils. It is supposed that a breeding programme could result in clones with the genetic ability for high uptake of specific heavy metals (Yasdani 1992).

A cadmium project is under planning in order to investigate the Cd fluxes in the soil-plant system with willow, containing sub-soil, top-soil, roots, stems, leaves, antropogenic deposition, and removal with harvested biomass. As one step in this planning, a seminar on '*Salix* as cadmium filter' was held in Uppsala 1995 in order to summarise the so far known facts in this matter (Göransson 1996).

Conclusions

So far, the experiences and results indicate that willow vegetation filters could be applied for treatment of municipal wastewaters and sewage sludges. Willows might also be used for purification of heavy metal contaminated soils. It is environmentally feasible to recirculate and utilize the residual products. Apart from neutralising harmful components, the vegetation filters also produce wood fuels for energy purposes. This combination of purification and production is positive for the environment also from the viewpoint of air pollution. Willow wood is in itself CO_2-neutral and otherwise less polluting than fossil fuels, and it can in many aspects be used as a substitute for natural gas, mineral oil and coal.

According to the examples on economic calculations given above concerning sludge and wastewater treatment, the conclusions to be drawn are that a system using willow crops as vegetation filters, thus combining purification and biomass production, seems to be an economically realistic alternative compared with conventional techniques.

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