WASTEWATER TREATMENT IN MULTIFUNCTIONAL BIOENERGY SYSTEMS

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ABSTRACT

This paper presents one concept of multifunctional bioenergy systems –the use of willow vegetation filters for the treatment of nutrient rich municipal wastewater and drainage water in Sweden. The concept is evaluated considering cost and efficiency in water treatment compared to alternative options. The concept is also evaluated from a farmer and energy sector point of view, where biomass supply costs and land use efficiency are in focus.

Wastewater irrigation will reduce willow cultivation costs in two ways, by increased biomass yields and by eliminating, or reducing, commercial fertilizers requirements. Compared to conventional cultivation methods, the land-use efficiency increases 30-100% when nutrient rich wastewater is used for irrigation.

The wastewater treatment efficiency (nitrogen and phosphorus removal) of willow vegetation filters is high. For municipal wastewater, the estimated treatment cost is lower than for conventional treatment in sewage treatment plants. In the case of drainage water treatment, the cost is in most cases estimated to be higher than for the alternative treatment option using restored wetlands. The reductions in willow cultivation cost are in most regions smaller than the cost difference between restored wetlands and willow vegetation filters.

When the value of water treatment is included, willow vegetation filters for municipal wastewater treatment have negative production costs. When willow vegetation filters are used for treatment of polluted drainage water, the biomass production cost will be reduced or increased depending on system design and geographic location in Sweden. Willow plantations that are established as buffer strips along open streams can provide biomass at approximately half the cost when the economic value of N retention is included.

1 INTRODUCTION

Biomass has the potential to become one of the major global primary energy sources during the next century (see [1] for a review of 17 studies of the global bioenergy potential). An extensive implementation of modern bioenergy systems is considered one path towards meeting low stabilisation targets for atmospheric CO_2. The European Commission White Paper on renewable energy [2] sets an overall EU target of doubling the contribution of renewables by 2010 (from 5,4 percent 1995 to 11,5 percent of total energy consumption) with some 85 percent of the renewables being bioenergy. Part of the expansion of bioenergy supply is suggested to be managed through increased use of biomass residues such as logging residues, straw, and organic waste for biogas production. But energy crops production is considered a key part of the Commission plan. Up to 10 million hectares of cropland is expected to be required in 2010, contributing half the bioenergy supply.

If located, designed and managed wisely, energy crop plantations can generate local environmental services. Examples of such multifunctional bioenergy systems[1] are willow vegetation filters for treatment of polluted water, plantations for preventing soil erosion (shelter belts), removal of cadmium from contaminated arable land (phytoremediation), increased soil carbon accumulation and soil fertility. Another type of a multi-functional biomass production system is logging residue recovery and wood ash recirculation, which could generate various additional environmental benefits in a forest ecosystem such as reduced N leaching and acidification [3]. Analyses of multifunctional bioenergy systems in the Swedish context reveal that the overall environmental benefits could be substantial [4-6]. When the economic value of such services is considered, the cost of large quantities of biomass could be reduced by more than 50 percent, thus affecting future market conditions for biomass in Sweden.

This paper presents one concept of multifunctional bioenergy systems –the use of willow vegetation filters for the treatment of nutrient rich municipal wastewater and drainage water in Sweden. Irrigation of willow with nutrient rich municipal wastewater and drainage water, can lead to substantially improved productivity and at the same time address pollution of ground water and eutrophication of rivers, lakes and seas. Thus, the concept is an attractive option for both farmers (lower biomass production costs) and sewage treatment plant operators (lower water treatment cost). The concept could also provide significant benefits for the society, especially in regions facing problems with nutrient polluted surface and ground water.

2 WILLOW VEGETATION FILTER CHARACTERISTICS

2.1 Treatment efficiency

The purification efficiency of willow vegetation filters has been demonstrated in several countries, e.g. Sweden, Poland, Denmark, and Estonia [7]. Currently, there are about five municipalities in Sweden which are utilising willow vegetation filters as a complement to conventional wastewater treatment methods. When wastewater percolates through the soil the root system takes up 75-95% of nitrogen (N) and phosphorus (P) in the wastewater [4]. The nutrient content in municipal wastewater corresponds fairly well to the nutrient requirements in willow cultivation. An annual municipal wastewater load of 600 mm, containing about 100 kg N, 20 kg P, and 65 kg K, will supply not only the required water, but also the requirements for N and other macro-nutrients [7]. The willow filter systems should be regarded as a complementary treatment step in existing conventional sewage treatment plants, primarily for nutrient removal. The wastewater is pumped to the willow vegetation filter after secondary treatment, before ordinary chemical P precipitation so that the nutrient is recirculated in the willow plantation. This approach reduces the risk of spreading pathogens [7].

The concept of using willow vegetation filters for the treatment of N-polluted drainage water has been tested in a large-scale field trial in southern Sweden since 1993 [8]. A one-hectare storage pond received drainage water from about 700 hectare of intensively cultivated and tile-drainaged land (sandy soils, heavily fertilized and irrigated, used for the production of annual crops such as potato, rape, wheat and rye). Water from the storage pond was subsequently used for irrigation of a three-hectare willow plantation, using a furrow system for water distribution. Results from the field trial show that the nitrate concentration in the drainage water was significantly reduced when passing the vegetation filter. The average water load amounted to around 1,600 mm yr^{-1}, containing around 185 kg N [8]. An improved cleaning efficiency was projected attainable under more careful matching of N load with the requirements of the willow plantation. A suggestion was that, in a long-term perspective, the yearly water load should not exceed 900 mm yr^{-1}, containing around 100 kg N.

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[1] We define multi-functional biomass production systems as systems that, besides producing biomass, also generate additional environmental services.

Another, more extensive method of reducing N leaching from arable land is by using willow plantations as buffer strips along open streams. This concept can be suitable when fields are lacking tile-drainage systems and the drainage water is not concentrated in a few, specific flows. The efficiency of N retention depends on water flow pathways controlling the transport of nutrients through the landscape, and the width of the buffer zone. N retention increases with increasing buffer width up to a width of about 25 m, where often more than 70 percent of the total N content is removed from the water flow. Increasing the buffer strip width further leads to marginal increases in N removal [4]. Thus, a suitable strategy is to establish willow plantations with a width of about 50 metres where half of the width is harvested at a time, leading to a continuous high uptake of nutrients. The N removal per hectare is estimated to be, on average, 70 kg per year [4].

2.2 Biomass yield response

A previous study by Lindroth and Båth [9] shows that water deficiency is often a growth-limiting factor in willow cultivation, even in countries like Sweden with significant rainfall all year around. The regional variation in biomass yields can be significant due to differences in water supply during the vegetation period. For example, the willow yield in conventional rain-fed plantations in south-east Sweden is normally around 50 to 60 percent of those in south-west Sweden, due to a lower rainfall in the summer season. Thus, the biomass yield response to wastewater irrigation will be more significant in regions with relatively low precipitation during the vegetation period. Wastewater irrigation is here estimated to increase the yields by 4 to 8 Mg DM ha^{-1} yr^{-1}, or 30 to 100 percent compared to rainfed willow plantations (Table 1). Biomass yields in conventional rainfed plantations refer to well managed plantations on good soils, excluding the first harvest after plantation establishment where the harvest is around 40% lower than for subsequent rotations.

Table 1. Estimated biomass yield in conventional rain-fed and wastewater irrigated willow plantations, respectively, in different Swedish regions.[a]

Region	Biomass yield		Yield increase	
	Conventional rain-fed plantations Mg DM ha^{-1} yr^{-1}	Wastewater irrigated plantations Mg DM ha^{-1} yr^{-1}	Mg DM ha^{-1} yr^{-1}	%
South-west Sweden	14	18	+ 4	+ 30
South-east Sweden	8	16	+ 8	+ 100
Central Sweden	10	16	+ 6	+ 60

[a] Estimations based on data from [9].

3 ECONOMICS

Below, the economic value of producing willow in vegetation filters, instead of in conventional cultivation, is estimated using the substitution cost method. The substitution cost describes the cost of providing the same environmental service, using another relevant method [5]. Direct costs and savings for the farmer, and benefits from yield increases are also estimated. Capital costs have been calculated using a 6% real discount rate, and the exchange rate was taken to be €1 = SEK 10. The lower heating value of willow is set to 17 GJ Mg^{-1} DM. The average biomass yield in conventional plantations without irrigation is set to 10 Mg DM ha^{-1} yr^{-1}. The average willow production cost is about €3.2 per GJ biomass (excluding transportation costs).

3.1 Municipal wastewater treatment

The economic value of municipal wastewater treatment in willow vegetation filters is calculated based on the estimated treatment cost reductions for sewage treatment plants avoiding conventional P and N treatment.

The treatment cost of municipal wastewater, considering N and P removal, is normally significantly lower in vegetation filters than in conventional treatment plants. Under Swedish conditions, the treatment cost of municipal wastewater in willow filters has in a previous study been estimated to about €5-12 per kg N, which can be compared to €7-18 per kg N in conventional treatment plants (variation due to local conditions) [10]. The treatment cost for willow filters is €5-9 per kg N if only wastewater produced during the summer months is treated. If wastewater produced during the whole year is treated, the cost is higher (€9-12 per kg N) due to additional costs for intermediate storage ponds. The cost calculations include irrigation through a pump-pipe system with a maximum length of the feed pipe to the willow plantation of 5 km, and the cost of all technical equipment, labour and energy use. The size of the filters was assumed to be 10 or 50 hectare [10]. Based on these cost calculations, the cost of wastewater treatment is here estimated to be reduced by, on average, €4-6 per kg N considering the summer option, and €1-3 per kg N considering the whole year option, respectively.

Practical experiences from Enköping municipality, which are utilising a 80 hectare willow plantation for wastewater treatment (whole year operation), indicate lower treatment costs than those presented above for the vegetation filter option and the conventional treatment option [11]. However, the cost savings per kg N removed is in the middle of the range assumed above, or around €1.5 per kg N considering the whole year option.

The generation of sewage sludge will also be significantly reduced when willow vegetation filters are used, leading to additional cost savings. Sewage sludge generation is estimated to be reduced by 50 to 80 percent, or 15 to 25 kg sludge per kg N. The cost of deposition of sewage sludge on landfills in Sweden is estimated at, on average, €70 per Mg sludge (including deposition tax at about €30 per Mg) [12]. Based on this, the economic value of reduced sewage sludge generation will be about €1.4 and €0.7 per kg N for the whole year option and summer option respectively.

Wastewater irrigation will reduce willow cultivation costs in two ways, by increasing biomass yields and by substituting for commercial fertilizers. The total cost savings for farmers have been estimated at €180-280 ha^{-1} yr^{-1}, depending on the size of biomass yield response (Table 1) [6]. The cost savings are equivalent to €1.8-2.8 per kg N, assuming that about 100 kg N will be removed per hectare of willow plantation. The higher cost saving refer to an increase in biomass yield of 8 Mg DM ha^{-1} yr^{-1}, and the lower cost saving to an increase in biomass yield of 4 Mg DM ha^{-1} yr^{-1}.

In Table 2, the economic value of municipal wastewater treatment in willow vegetation filters are presented in terms of reduced costs per kg N removed, and reduced costs per GJ of willow biomass produced. For comparison, the average production cost of willow in conventional cultivation without irrigation is about €3.2 per GJ biomass (excluding transportation costs).

Table 2. Economic value of municipal wastewater treatment in willow vegetation filters in different Swedish regions[a].

Region	Changed wastewater treatment costs [b]		Changed cultivation costs [c]	Total economic value [d]	
	Summer option [e]	Whole year option [f]		Summer option [e]	Whole year option [f]
	€ per GJ biomass (€ per kg N)	€ per GJ biomass (€ per kg N)	€ per GJ biomass (€ per kg N)	€ per GJ biomass (€ per kg N)	€ per GJ biomass (€ per kg N)
South-west	-3.4	-2.0	-1.1	-4.5	-3.1
Sweden	(-5.7)	(-3.4)	(-1.8)	(-7.5)	(-5.2)
South-east	-3.4	-2.0	-1.7	-5.1	-3.7
Sweden	(-5.7)	(-3.4)	(-2.8)	(-8.5)	(-6.2)
Central	-3.4	-2.0	-1.4	-4.8	-3.4
Sweden	(-5.7)	(-3.4)	(-2.3)	(-8.0)	(-5.7)

[a] The wastewater application corresponds to 100 kg N ha^{-1} yr^{-1}.
[b] The alternative N and P treatment is in conventional wastewater plants. Based on average treatment costs which could vary due to local conditions (see text).
[c] Including increased biomass yields and reduced costs of fertilization.
[d] Negative sign indicates cost reduction.
[e] Summer option means treatment of wastewater produced during the vegetation period.
[f] Whole year option means treatment of wastewater produced during the whole year and thus include intermediate storage ponds.

3.2 Polluted drainage water treatment

The economic value of the treatment of polluted drainage water in willow vegetation filters is calculated based on the estimated treatment cost using restored wetlands. Wetland restoration is an option for eutrophication reduction that is a commonly used in Sweden today. The cost of N mitigation through restoration of wetlands in Sweden has been estimated by [13] at €2 to €6 per kg N, depending on local conditions.

The estimated cost of the drainage water irrigation systems include costs for a pump-pipe irrigation system, storage pond, all technical equipment, labour and energy use [10]. The size of the storage pond is here estimated to vary regionally depending on the annual precipitation and N content in the drainage water. In the more dry areas with relative high N leaching, e.g. south-east Sweden, smaller storage ponds are required per hectare of willow vegetation filter in order to supply the drainage water containing 100 kg N, compared to areas with higher precipitation and lower N leaching, e.g. in central Sweden [6]. One way of reducing the cost of irrigation is to reduce the size of storage ponds. If, for example, the size is reduced by 65%, this will reduce the irrigation cost by 40%. This will also result in that only a part of the drainage water will be treated, mainly the drainage water produced during the summer season. The major part of the drainage water produced during the winter season will pass the pond without being used for irrigation. Here, two options of drainage water irrigation are included, (i) the whole year option where all drainage water produced during the whole year is treated, and (ii) the summer option where drainage water produced only during the summer season is treated (Table 3).

Like in the case of municipal wastewater irrigation, the cultivation cost will be reduced due to increased biomass yields and reduced fertilizer costs. The reduced fertilizer costs will, however, be somewhat lower than in the case of municipal wastewater irrigation. The reason is that additional P and K fertilization is needed due to a less optimal nutrient composition, with excess N compared to P and K.

Table 3. Economic value of drainage water treatment in willow vegetation filters in different Swedish regions [a]. Reduced costs are indicated by (-) and increased costs by (+).

Region	Changed drainage water treatment costs [b]		Changed cultivation costs [c]	Total economic value	
	Summer option [d]	Whole year option [e]		Summer option [d]	Whole year option [e]
	€ per GJ biomass (€ per kg N)	€ per GJ biomass (€ per kg N)	€ per GJ biomass (€ per kg N)	€ per GJ biomass (€ per kg N)	€ per GJ biomass (€ per kg N)
South-west	-0.2	+1.3	-0.9	-1.1	+0.4
Sweden	(-0.3)	(+2.2)	(-1.6)	(-1.9)	(+0.6)
South-east	-0.2	+0.9	-1.5	-1.7	-0.6
Sweden	(-0.4)	(+1.6)	(-2.6)	(-3.0)	(-1.0)
Central	+0.5	+2.9	-1.2	-0.7	+1.7
Sweden	(+0.9)	(+4.9)	(-2.1)	(-1.2)	(+2.8)

[a] The drainage water application corresponds to 100 kg N ha^{-1}.
[b] The alternative N treatment is in restored wetlands. Based on average treatment costs which could vary due to local conditions (see text).
[c] Including increased biomass yields and reduced costs of fertilization.
[d] Summer option means treatment of drainage water produced during the vegetation period and include storage ponds which are 65% smaller in size compared with those used in the whole year option.

[e] Whole year option means treatment of drainage water produced during the whole year and include storage ponds which are 65% larger in size compared with those used in the summer option.

The economic value of the treatment of polluted surface water and shallow ground water in buffer strips along open streams is, like in the case of drainage water irrigation, calculated based on the estimated treatment cost using restored wetlands. The cultivation cost is affected in different directions when willow plantations are used as buffer strips. The N fertilizers cost is reduced somewhat but the harvesting cost is estimated to increase by a similar amount, due to the fact that the harvested buffer strip area is smaller than for conventional cultivation [5].

Table 4. Economic value of willow buffer strips along open streams [a]. Reduced costs are indicated by (-) and increased costs by (+).

Changed run off water treatment costs [b]	Changed cultivation costs [c]	Total economic value
€ per GJ biomass (€ per kg N)	€ per GJ biomass (€ per kg N)	€ per GJ biomass (€ per kg N)
-1.6 (-4.0)	+/-0 (+/-0)	-1.6 (-4.0)

[a] The run of water application corresponds to 70 kg N ha^{-1}.
[b] The alternative N treatment is in restored wetlands. Based on average treatment costs which could vary due to local conditions (see text).
[c] Including reduced costs of fertilization and increased costs of harvesting.

3.3 Summary of changed biomass costs

The estimated biomass production costs in willow vegetation filter systems (including the value of water treatment) are presented in Table 5. For comparison, the production costs in conventional willow cultivation are also shown. As can be seen, willow vegetation filters for municipal wastewater treatment have negative production costs. This indicates that the estimated economic value of the environmental services provided is higher than the willow cultivation costs. When willow vegetation filters are used for treatment of polluted drainage water, the biomass production cost will be reduced considering the summer option. Considering the whole year option, however, the biomass production cost will increase in south-west and central Sweden. Willow plantations that are established as buffer strips along open streams can provide biomass at approximately half the cost when the economic value of N retention is included.

Table 5. The estimated biomass production cost in willow vegetation filter systems in different Swedish regions when the estimated economic value of polluted water treatment is included [a]. Negative production costs are indicated by (-).

Region	Conventional willow plantations[b]	Willow vegetation filters for municipal wastewater treatment[b]		Willow vegetation filters for polluted drainage water treatment[b]		Willow buffer strips for reduced N leaching
		Summer option [c]	Whole year option [d]	Summer option [c]	Whole year option [d]	
	€ per GJ biomass	€ per GJ biomass	€ per GJ biomass	€ per GJ biomass	€ per GJ biomass	€ per GJ biomass
South-west Sweden	3.0	-1.5	-0.1	1.9	3.4	1.4
Sout- east Sweden	3.4	-1.7	-0.3	1.7	2.8	1.8
Central Sweden	3.2	-1.6	-0.2	2.5	4.9	1.6

[a] Based on Tables 2-4.
[b] Excluding costs for biomass transportation [6].
[c] Treatment of polluted water produced during the vegetation period.
[d] Treatment of polluted water produced during the whole year.

4 CONCLUSIONS AND DISCUSSION

This paper shows that, when the estimated economic value of the environmental service provided (removal of N and P in water) is included, most applications of the willow vegetation filter concept can supply biomass at significantly reduced costs. In the case of municipal wastewater treatment, this is due to both reduced willow cultivation costs and the fact that willow vegetation filters provide a treatment option that is lower in cost than conventional treatment at sewage plants. In the case of polluted drainage water treatment, the alternative treatment option (restored wetlands) is in most cases lower in cost than the willow vegetation filter option. However, the benefits of reduced cultivation costs can in many situations outweigh the extra cost of choosing willow vegetation filters. Willow cultivation as buffer strips along open streams can supply biomass at about half the cost in conventional plantations.

One key issue when evaluating the attractiveness of willow vegetation filters –and multifunctional bioenergy systems in general– is how to distributre the economic value of the environmental service among the different actors involved in the project. The case of willow vegetation filters for municipal wastewater treament can be used as an example. Here, the farmer benefits from reduced willow production costs, but also faces the risk of long-term commitments with less flexibility in land use. This may require that an additional risk premium is paid to the farmer in order to make the willow option more attractive than, e.g., production of annual food crops. The operator of the sewage treatment plant should be willing to pay for the willow vegetation filter system, including a certain land rent paid to the farmer, as long as the total cost is still significantly lower than the cost of the conventional treatment option. The attractiveness of the concept also depends on the market prospects for bioenergy. Here, the farmer may rely on that the long-term market prices will be acceptable, or negotiate for long-term contracts with, e.g., a heating plant operator (which may require that the pre-defined price is somewhat lower than the expected market prices, alternatively finds motivation in a reliable long-term biomass supply). The heating plant operator may be even more involved in the project –the wood ash can preferably be returned to the willow plantation– and thus which to contribute to the long-term viability of the project.

Several data used in the calculations are uncertain, as the costs could vary significantly due to local conditions. However, despite these uncertainties, the results clearly indicate that the concept of willow vegetation filters has the potential to address two of our most serious environmental problems today, water pollution and climate change. Thus, policy measures to stimulate the introduction of such multifunctional bioenergy systems seem to be an effective tool in reducing CO_2 emissions to the atmosphere and N emissions to waters. A great challenge when creating such measures lies in the harmonization of the different policies in the energy, environmental and agricultural fields.

5 ACKNOWLEDGEMENTS

We gratefully acknowledge the economic support provided by The Swedish Energy Agency.

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