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The prospects for willow plantations for wastewater treatment in Sweden

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Abstract

The concept of willow vegetation filters for the treatment of nutrient-rich wastewater has the potential to address two of our most serious environmental problems today —water pollution and climate change— in a cost-efficient way. Despite several benefits, including high treatment efficiency, increased biomass yields, improved energy and resource efficiency, and cost savings, willow vegetation filters have so far only been implemented to a limited degree in Sweden. This is due to various kinds of barriers, which may be the result of current institutional, structural and technical/geographical conditions. This paper discusses the prospects of a more widespread utilisation of willow plantations for wastewater treatment in Sweden, including existing incentives and barriers, based on current knowledge and experience.

Keywords: Vegetation filters; Costs; Energy balance; Carbon offset; The Enköping model

1. Introduction

If located, designed and managed wisely, energy crop plantations can, besides producing renewable energy, also generate local environmental benefits. Examples are willow plantations leading to soil carbon accumulation, increased soil fertility, reduced nutrient leaching and improved hunting potential, representing more general benefits. Another category of willow plantations are those designed for dedicated environmental services, such as shelter belts for the prevention of soil erosion, plantations for the removal of cadmium from contaminated arable land (phytoextraction), and vegetation filters for the treatment of nutrient-rich, polluted water. Analyses of *multifunctional bioenergy systems*[1] in the Swedish context reveal that the overall environmental benefits may be substantial [1–4]. When the economic value of such services is considered, the cost of large quantities of biomass could be significantly reduced, 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. The irrigation of willow with nutrient-rich municipal wastewater and drainage water can lead to substantial yield increases and at the same time reduce the pollution of groundwater and eutrophication of rivers, lakes and the marine environment at relatively low costs. Thus, the concept is an attractive option for both farmers (lower biomass production costs) and sewage treatment plant operators (lower water treatment costs). The concept could also provide significant benefits for the community at large, especially in regions facing problems with nutrient-polluted surface and groundwater. In this paper, the prospects for willow vegetation filters are discussed from a multidisciplinary perspective based on current knowledge, including aspects such as treatment efficiency, net energy performance, economics and potential incentives and barriers to large-scale implementation.

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[1]We define multifunctional bioenergy systems as systems that, besides producing biomass, are located, designed and managed to also generate dedicated additional environmental services that are fully exploited.

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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 [5,6]. Currently, there are about five municipalities in Sweden utilising willow vegetation filters as a complement to conventional wastewater treatment methods, primarily for nutrient removal. Some of these have been in use since the early 1990s [7]. Two concepts exist, *the summer option* where only wastewater produced during the summer months is treated, and *the whole year option* in which wastewater produced during the winter months is stored in ponds for interim storage. The wastewater is pumped to the willow vegetation filter, or to the storage ponds, after biological (secondary) treatment, but before ordinary chemical P precipitation, so that the nutrient is recirculated to the willow plantation.

The average nutrient content in Swedish municipal wastewater normally 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 of N and other macronutrients [5]. The root systems will then take up 75–95% of the nitrogen (N) and phosphorus (P) in the wastewater [2]. The generation of sewage sludge will also be significantly reduced when willow vegetation filters are used, by, on average, 50% in the summer option and by 80% in the whole year option [4]. The life span of the vegetation filters is estimated to be 20–25 years, and results from long-term field trials indicate no problems of increased salinisation or contamination of the soil [6].

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]. Water from tile drainage systems was collected in a storage pond. The water was subsequently used for irrigation of a 3-hectare (ha) 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 after passing the vegetation filter.

Another, more extensive method of reducing N leaching from arable land consists of willow plantations that are cultivated 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% of the total N content is removed from the water flow [2]. Thus, a 50 m wide willow buffer strip, in which half of the width is harvested at a time, appears to be a design that could provide a continuous, high uptake of nutrients.

2.2. Biomass yield response

Water availability is often overlooked in commercial willow cultivation, despite the fact that it is one of the most important factors for high biomass yields [7]. Lindroth and Båth [9] show that water deficiency is often a growth-limiting factor in willow cultivation, even in countries like Sweden with significant precipitation throughout the year. The regional variation in biomass yields can be significant due to differences in water availability during the vegetation period. For example, the willow yield in conventional, rain-fed plantations in southeast Sweden is normally only about 50–60% of those in southwest Sweden, due to a lower rainfall in the summer season. Obviously, 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 4–8 t DM ha^{-1} yr^{-1}, or 30–100% compared to average yields for well-managed, rain-fed willow plantations on good soils (Table 1).

3. Net energy performance of willow vegetation filter applications

The pumping of irrigation water, and also the establishment of the wastewater irrigation system, require energy inputs. On the other hand, recycling of the nutrients in wastewater reduces the need for commercial fertilisers and hence also the energy input for fertiliser production.

Table 1
Estimated biomass yield in conventional rain-fed and wastewater irrigated willow plantations, in various regions of Sweden[a]

Region	Biomass yield Conventional rain-fed plantations[b] (t DM ha^{-1} yr^{-1})	Wastewater irrigated plantations (t DM ha^{-1} yr^{-1})	Yield increase t DM ha^{-1} yr^{-1}	%
Southwest Sweden	14	18	+4	+30
Southeast Sweden	8	16	+8	+100
Central Sweden	10	16	+6	+60

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

[b]Biomass yields in conventional rain-fed plantations refer to well managed plantations on good soils, excluding the first harvest after establishment when the harvest is about 40% lower than for subsequent rotations.

Table 2
The energy balance of using willow filter systems for treatment of municipal wastewater and drainage water from intensively cultivated cropland[a]

	Energy cost (−)/saving (+) ($GJ\,ha^{-1}\,yr^{-1}$)	Net yield increase[b] ($GJ\,ha^{-1}\,yr^{-1}$)	Net energy balance ($GJ\,ha^{-1}\,yr^{-1}$)
Municipal wastewater treatment			
Irrigation[c]	−12.5		
Substitution of conventional treatment[d]	+0.8		
Reduced N fertiliser requirement	+4.5		
Reduced P and K fertiliser requirement	+0.5		
Total	−6.7	68–136	+ 61 to +129
Drainage water treatment			
Irrigation[e]	−2.7		
Reduced N fertiliser requirement	+4.5		
Total	+1.8	68–136	+ 70 to +138

[a]Based on Berndes and Börjesson [10]. The energy balance is estimated based on a reference case where willow is cultivated without irrigation and using commercial fertilisers. Conventional methods for treatment of municipal wastewater. No treatment of drainage water.
[b]Data from Table 1. Lower heating value (LHV) of $17\,GJ\,t^{-1}$ DM. The additional energy input in increased harvesting effort is estimated to be 0.2–0.4 $GJ\,ha^{-1}\,yr^{-1}$.
[c]Including direct energy use for pumping, $12\,GJ\,ha^{-1}\,yr^{-1}$, and indirect energy input for the construction of the irrigation system, $0.5\,GJ\,ha^{-1}\,yr^{-1}$.
[d]Energy savings (direct and indirect) for replacement of conventional N removal, $0.65\,GJ\,ha^{-1}\,yr^{-1}$, and P removal, $0.15\,GJ\,ha^{-1}\,yr^{-1}$, in wastewater treatment plants.
[e]Including direct energy use for pumping, $2.3\,GJ\,ha^{-1}\,yr^{-1}$, and indirect energy input for the construction of the irrigation system, $0.4\,GJ\,ha^{-1}\,yr^{-1}$.

Additional energy savings are achieved by the substitution of N and P removal in conventional treatment plants by the willow filter system. Furthermore, the estimated yield increase of 4–8 t DM $ha^{-1}\,yr^{-1}$ corresponds to a significant amount of additional biomass for energy. In Table 2, the energy balance of using willow vegetation systems is summarised, based on data from Berndes and Börjesson [10].

In municipal wastewater treatment, the combined energy savings are slightly less than half of the energy input for water pumping and irrigation system establishment. In drainage water treatment, the energy savings are, by contrast, almost twice the energy input needed. However, both vegetation filter systems have a significant, positive, net energy gain due to the expected yield increase. The additional energy inputs arising from increased harvesting operations are fairly small. The overall net energy yield in conventional willow production in Sweden is, on average, about $170\,GJ\,ha^{-1}\,yr^{-1}$ [11]. Thus, willow vegetation filter systems would be likely to reach an overall net energy yield that is well above $200\,GJ\,ha^{-1}\,yr^{-1}$.

4. Economic performance of willow vegetation filter applications

The economic value of wastewater treatment in willow vegetation filters is estimated using the substitution cost method. The substitution cost describes the cost of providing the same environmental service, using a relevant, alternate method [3]. 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€ = 10 SEK. The average biomass yield in conventional plantations without irrigation is set to 10 t DM $ha^{-1}\,yr^{-1}$. The life span of the willow plantations is set to 24 years and the estimates of production costs exclude the current subsidies for willow production given in Sweden and the EU. The question of how a changed biomass cost in various vegetation filters will affect the carbon mitigation cost is also discussed.

4.1. Treatment of municipal wastewater in willow vegetation filters

Willow vegetation filters for municipal wastewater treatment are attractive from an economic point of view (Table 3). This is due to reduced willow cultivation costs and also to the fact that willow vegetation filters provide a treatment option that is lower in cost than conventional treatment at sewage plants. In the summer option, the main economic benefit comes from reduced nitrogen treatment costs, whereas in the whole year option, the cost avoided for sewage sludge treatment could be almost equal to the reduced cost for nutrient treatment. Practical experience from the Enköping municipality, which utilises an 80-ha willow plantation for wastewater treatment (whole year operation), indicates lower treatment costs than those presented in Table 3 for the vegetation filter option as well as for the conventional treatment option [12]. However, the cost savings per kg N removed is in the middle of the range presented here. Regarding the changed cultivation costs, 50–70% of the reduction refers to the net value of increased biomass yields (considering increased harvesting costs), whereas the remaining reduction refers to reduced fertilisation costs.

Table 3
Economic value of municipal wastewater treatment in willow vegetation filters in different regions of Sweden[a]

Region	Changed wastewater treatment costs[b]		Changed biomass production costs[c]	Total economic value[d]	
	Summer option[e] € GJ^{-1} biomass (€ kg^{-1} N)	Whole year option[f] € GJ^{-1} biomass (€ kg^{-1} N)	€ GJ^{-1} biomass (€ kg^{-1} N)	Summer option € GJ^{-1} biomass (€ kg^{-1} N)	Whole year option € GJ^{-1} biomass (€ kg^{-1} N)
Southwest Sweden	−3.4 (−5.7)	−2.0 (−3.4)	−1.1 (−1.8)	−4.5 (−7.5)	−3.1 (−5.2)
Southeast Sweden	−3.4 (−5.7)	−2.0 (−3.4)	−1.7 (−2.8)	−5.1 (−8.5)	−3.7 (−6.2)
Central Sweden	−3.4 (−5.7)	−2.0 (−3.4)	−1.4 (−2.3)	−4.8 (−8.0)	−3.4 (−5.7)

[a]The wastewater application corresponds to 100 kg N ha^{-1} yr^{-1}. Cost calculations include a pump-pipe irrigation system with a 5 km feed pipe, storage pond (whole year option), all technical equipment, labour and energy use [4,13].

[b]The alternative N and P treatment is done in conventional wastewater plants. Based on average treatment costs, which could vary between 7 and 18€ kg^{-1} N depending on local conditions [13]. The alternative treatment cost of sewage sludge is estimated to be 70€ t^{-1} sludge, as deposit in landfills [14].

[c]Including increased biomass yields, increased harvesting costs and reduced costs of fertilization [4].

[d]Negative sign indicates cost reduction.

[e]Summer option means treatment of wastewater produced during the vegetation period. The average treatment cost is estimated to vary between 5 and 9€ kg^{-1} N depending on local conditions [13]. The generation of sewage sludge is reduced by 50%, or 15 kg sludge kg^{-1} N.

[f]Whole year option means treatment of wastewater produced during the whole year and thus includes ponds for interim storage. The average treatment cost is estimated to vary between 9 and 12€ kg^{-1} N depending on local conditions [13]. The generation of sewage sludge is reduced by 80%, or by 25 kg sludge kg^{-1} N.

4.2. Treatment of polluted drainage water in willow vegetation filters

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 the reduction of eutrophication often used in Sweden today. Compared with this treatment option, the willow vegetation filter option is sometimes lower and sometimes higher in cost (Table 4). This depends on local conditions and the required size of the ponds for interim storage, which strongly affect the costs of willow vegetation filters. The size of the storage ponds vary regionally depending on the annual precipitation and the content of N in the drainage water. In drier areas with relative high N leaching (e.g. southeast Sweden), smaller storage ponds are required per hectare of willow vegetation filter, compared to areas with higher precipitation and lower N leaching (e.g. in central Sweden) [4]. When drainage water produced during the vegetation period is treated (summer option), the storage ponds are also significantly smaller than when drainage water produced during the whole year is treated (whole year option).

As in the case of municipal wastewater irrigation, the biomass production cost will be reduced due to increased biomass yields and reduced fertiliser costs. Some 60–80% of the reduced production costs refer to the net value of increased biomass yields (including increased harvesting costs). Thus, the reduced fertiliser costs are somewhat lower than in the case of municipal wastewater irrigation, due to an inferior nutrient composition of the drainage water, with excess N compared to P and K (an additional fertilisation of P and K is needed).

4.3. Treatment of polluted surface water and shallow groundwater in buffer strips

The economic value of the treatment of polluted surface water and shallow groundwater in buffer strips along open streams is, as in the case of the 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 (Table 5). The cost of N fertilisers is reduced somewhat, but the harvesting cost is estimated to increase by a similar amount, due to the fact that the buffer strip area is smaller than for conventional cultivation [3]. No increase in yield is expected in buffer strips, compared with conventional plantations.

4.4. Summary of changed biomass costs

The estimated costs of biomass production in different willow vegetation filter systems (including the value of water treatment) are summarised in Table 6. For comparison, the production costs in conventional willow cultivation are also shown. As can be seen, when willow is cultivated as vegetation filters for municipal wastewater treatment the estimated production cost is negative. This indicates that the estimated economic value of the environmental services provided is higher than the cost of willow cultivation. When willow vegetation filters are used for the treatment of polluted drainage water, the biomass production cost will be reduced in the summer option. For the whole year option, the biomass production cost will increase in southwest 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 4
Economic value of drainage water treatment in willow vegetation filters in different regions of Sweden[a]

Region	Changed drainage water treatment costs[b]		Changed biomass production costs[c]	Total economic value	
	Summer option[d] € GJ^{-1} biomass (€ kg^{-1} N)	Whole year option[e] € GJ^{-1} biomass (€ kg^{-1} N)	€ GJ^{-1} biomass (€ kg^{-1} N)	Summer option[d] € GJ^{-1} biomass (€ kg^{-1} N)	Whole year option[e] € GJ^{-1} biomass (€ kg^{-1} N)
Southwest Sweden	−0.2 (−0.3)	+1.3 (+2.2)	−0.9 (−1.6)	−1.1 (−1.9)	+0.4 (+0.6)
Southeast Sweden	−0.2 (−0.4)	+0.9 (+1.6)	−1.5 (−2.6)	−1.7 (−3.0)	−0.6 (−1.0)
Central Sweden	+0.5 (+0.9)	+2.9 (+4.9)	−1.2 (−2.1)	−0.7 (−1.2)	+1.7 (+2.8)

Reduced costs are indicated by (−) and increased costs by (+).
[a]The drainage water application corresponds to 100 kg N ha^{-1}. Costs included are for a pump-pipe irrigation system, storage pond, all technical equipment, labour and energy use [4,13].
[b]The alternative N treatment is in restored wetlands. Based on average treatment costs of 4€ kg^{-1} N, which could vary between 2 and 6€ kg^{-1} N depending on local conditions [15].
[c]Including increased biomass yields, increased harvesting costs and reduced costs for fertilization.
[d]Summer option means treatment of drainage water produced during the vegetation period and includes storage ponds which are 65% smaller compared with those used in the whole year option.
[e]Whole year option means treatment of drainage water produced during the whole year and includes storage ponds which are 65% larger compared with those used in the summer option.

Table 5
Economic value of willow buffer strips along open streams[a]

Changed run-off water treatment costs[b] € GJ^{-1} biomass (€ kg^{-1} N)	Changed biomass production costs[c] € GJ^{-1} biomass (€ kg^{-1} N)	Total economic value € GJ^{-1} biomass (€ kg^{-1} N)
−1.6 (−4.0)	±0 (±0)	−1.6 (−4.0)

Reduced costs are indicated by (−) and increased costs by (+).
[a]The run-off water application corresponds to 70 kg N ha^{-1} [2–4].
[b]The alternative N treatment is in restored wetlands. Based on average treatment costs of 4€ kg^{-1} N, which could vary between 2 and 6€ kg^{-1} N depending on local conditions [15].
[c]Including reduced costs of fertilization and increased costs of harvesting.

Table 6
The estimated biomass cost in willow vegetation filter systems in different regions of Sweden, when the estimated economic value of polluted water treatment is included[a]

Region	Conventional willow plantations[b]	Willow vegetation filters for municipal wastewater treatment		Willow vegetation filters for polluted drainage water treatment		Willow buffer strips to reduce N leaching
		Summer option[c]	Whole year option[d]	Summer option[c]	Whole year option[d]	
	€ GJ^{-1} biomass	€ GJ^{-1} biomass	€ GJ^{-1} biomass	€ GJ^{-1} biomass	€ GJ^{-1} biomass	€ GJ^{-1} biomass
Southwest Sweden	3.0	−1.5	−0.1	1.9	3.4	1.4
Southeast 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

Negative production costs are indicated by (−).
[a]Based on Tables 3–5.
[b]Excluding costs for biomass transportation [4].
[c]Treatment of polluted water produced during the vegetation period.
[d]Treatment of polluted water produced during the whole year.

4.5. Carbon dioxide mitigation cost

Previous studies show that the CO_2 mitigation cost when fossil fuels are replaced by biomass is often most sensitive to changes in fuel costs [16]. Below, it is shown how, for various conversion technologies, the cost reductions in biomass production achieved in various willow vegetation filter applications will affect the CO_2 mitigation cost [17].

The analysis is based on the total reduction in CO_2 emissions (fuel-cycle CO_2 emissions) by substituting natural gas for the cogeneration of power and heat, and for stand-alone power production [16]. Cogeneration systems typically improve the efficiency of fuel use and reduce costs compared to the separate production of heat and power. However, the potential volume of cogeneration systems is limited by the availability of heat sinks.

The reference entity used is 1 GJ of power and 1 GJ of heat, since this is the highest ratio of produced power to heat for the cogeneration technology studied. For the additional power required for cogeneration plants with a power to heat ratio < 1.0, the power is assumed to be produced in condensing plants. A more extensive description of the prerequisites for the analysis is given in Refs. [16,17]. The price of natural gas is assumed to be 3.6 and 3.0 € GJ^{-1} fuel for cogeneration and condensing plants, respectively, excluding domestic Swedish taxes. The following systems are considered:

Cogeneration of power and heat

- A natural gas-fired cogeneration plant (Cogen-NG)—*Reference energy system.*
- A natural gas-fired condensing plant and a biomass-fired cogeneration plant with steam turbine (Cogen-Bio-ST).
- A biomass-fired cogeneration plant with integrated gasification and combined-cycle technology (Cogen-Bio-IGCC).

Stand-alone power production

- A natural gas-fired condensing plant (Condense-NG)—*Reference energy system.*
- A biomass-fired condensing plant with steam turbine (Condense-Bio-ST).
- A biomass-fired condensing plant with integrated gasification and combined cycle technology (Condense-Bio-IGCC).

Reductions in willow production cost will simultaneously lead to a reduction in the carbon dioxide mitigation cost when fossil fuels are replaced. The carbon mitigation costs correlate fairly well with the biomass costs, when natural gas for stand-alone power production and combined heat and power production is replaced (Fig. 1). Thus, the carbon mitigation cost is estimated to turn negative when natural gas is replaced by biomass from willow vegetation filters used for municipal wastewater treatment. When biomass from buffer strips and vegetation filters used for the treatment of polluted drainage water produced during the vegetation period (summer option)

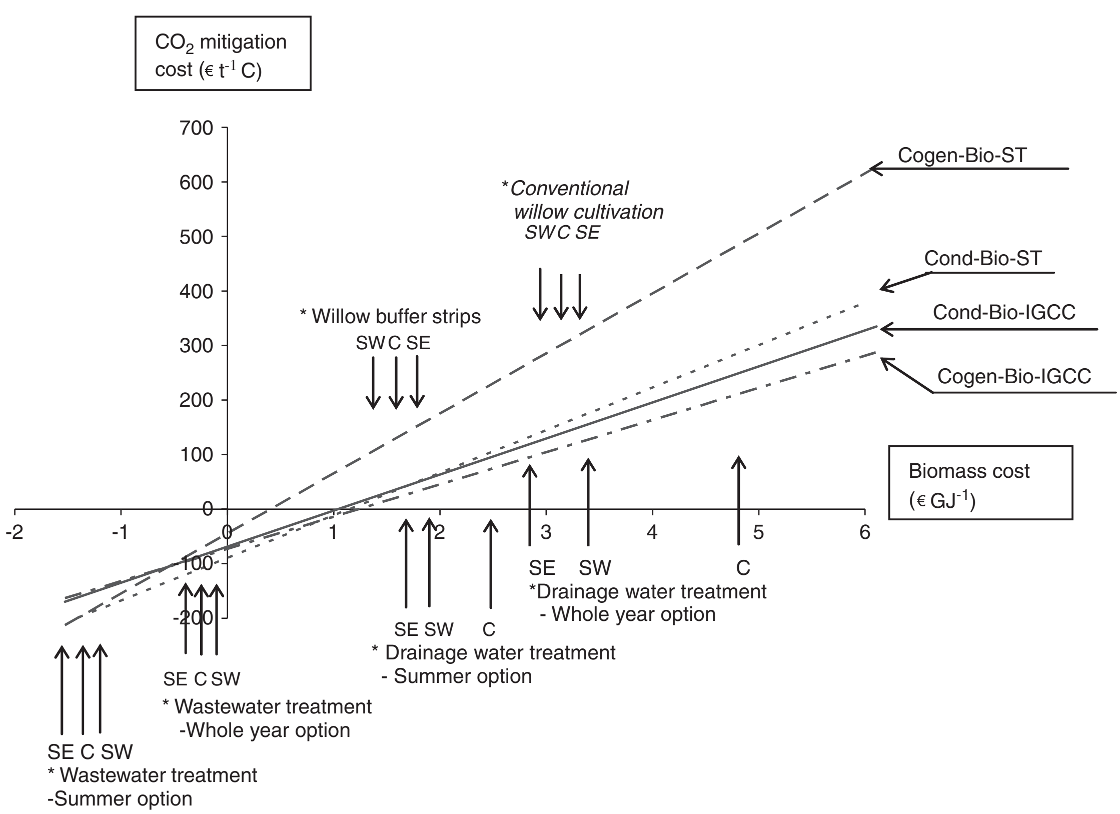

Fig. 1. CO_2 mitigation costs when biomass replaces natural gas for cogeneration of heat and power and for stand-alone power production, respectively, as a function of biomass cost. The cost of biomass produced in various multifunctional willow plantations in different regions in Sweden, as well as in conventional plantations, is indicated by arrows (SE = southeast, SW = southwest, and C = central Sweden).

replaces natural gas, the carbon dioxide mitigation cost is estimated to be reduced by 35–65%. However, when biomass comes from willow plantations irrigated with all the polluted drainage water that is produced during the whole year, the CO_2 mitigation costs will be similar (or significantly higher for central Sweden) to when biomass from conventional willow plantations is utilised.

Some of the data used and technology assumptions made here are uncertain, since uncertainties exist regarding new conversion technologies, fossil fuel prices, etc. Furthermore, preliminary results from measurements of greenhouse gas emissions from the willow vegetation filter in the Enköping case show that up to about 5–7% of nitrogen in the applied wastewater may be converted into nitrous oxide (N_2O) [18]. This counteracts some of the greenhouse gas reduction gained when the biomass replaces fossil fuels such as natural gas, roughly by 10% depending on the amount of nitrous oxide produced in the nitrogen treatment step in the conventional wastewater plant. However, despite these unknowns, the results obtained 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— in a cost efficient way.

5. Incentives and barriers

The extent to which willow vegetation filters will be implemented in the future depends on several factors. Different kinds of economical, institutional, structural and technical/geographical incentives and barriers exist that will affect different actors in positive or negative directions. These are discussed below. In addition, a description is given of a success story where the concept of municipal wastewater treatment in willow vegetation filters is applied on a large scale in the city of Enköping, located in central Sweden. The experience gained from Enköping may function as a model for the successful implementation of willow vegetation filters for municipal wastewater treatment.

5.1. Economic incentives and barriers

The implementation of willow vegetation filters will depend on how the costs and benefits are distributed among different actors (e.g., farmers, municipalities and the community in general). For example, a reduction in production costs makes it interesting for farmers to establish the willow plantation so as to provide an environmental service. This is the case for municipal wastewater treatment in willow vegetation filters (Table 7). On the other hand, when the production cost is increased, such as in the case of drainage water irrigation, the community may have to pay the farmer for the environmental service provided in order to provide an incentive. This may also be needed in the case of drainage water treatment in buffer strips, which normally do not lead to economic benefits for the farmer. One proposition is that subsidies are given to farmers who establish willow vegetation filters and buffer strips, and that the size of such subsides is correlated to the magnitude of the environmental service achieved. Today, subsidies are given for nitrogen mitigation measures, such as the establishment of catch crops, restoration of wetlands, etc.

When farmers establish willow vegetation filters for, for instance, municipal wastewater treatment, they face the risk of long-term commitments with less flexible 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. the 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 to the farmer, provided that the total cost is still significantly lower than the cost of conventional wastewater treatment.

The attractiveness of the concept of willow vegetation filters also depends on the market prospects for bioenergy. Here, the farmer may rely on long-term market prices being acceptable, or negotiate for long-term contracts with a biomass plant (which may require that the pre-defined price is somewhat lower than the expected market prices; alternatively the operator may find motivation in a reliable, long-term biomass supply). By applying long-term contracts, potential risks can be allocated between the farmer, who handles the production risks, and the biomass plant operator, who handles the price risks [19]. The biomass plant operator may become even more involved in the project. For example, the wood ash from a heat plant or heat/power plant can, to advantage, be returned to the willow plantation. Obviously, operators of such biomass plants would be very interested in the long-term viability of the project.

Table 7
The distribution of the costs and benefits of willow vegetation filters among farmers, municipalities and the community in general[a]

	Reduced costs-potential incentives	Increased costs-potential barriers
Municipal wastewater treatment—irrigation	Farmer and municipality (treatment plant)	
Drainage water treatment—irrigation	The community in general	Farmer
Drainage water treatment—buffer strips	The community in general	

[a]Based on Börjesson et al. [4].

5.2. Institutional incentives and barriers

Examples of institutional barriers to a large-scale implementation of willow vegetation filters (and willow production in general) are subsidies and regulations within the agricultural policy. Until recently (2004), the common agricultural policy (CAP) within the EU has counteracted Swedish national institutional incentives, such as carbon taxes on fossil fuels, leading to a cessation in the establishment of new willow plantations.

One example is for the subsidy of the establishment willow plantations, which was introduced in Sweden in 1991, but was halved when Sweden joined the EU. An establishment subsidy is important in reducing the negative liquidity during the first rotation period of 3–5 years, and thereby the economic risk to the farmer [20]. The CAP has also affected the prerequisite for willow cultivation in other ways. The amount of mandatory set-aside land (i.e., the area that farmers have to withdraw from food crop cultivation in order to obtain subsidies for grain and oil seed cultivation) has varied considerably from year to year. This leads to reduced willingness to establish long-term willow plantations, especially among grain producers with a high equipment capacity for grain cultivation, since they obtain the highest profitability for willow cultivation on mandatory set-aside land, but not on other land [21].

A long-term agricultural policy ensuring that the prerequisites for perennial energy crop cultivation are stable, in combination with a harmonisation with demand-oriented incentives within energy and environmental policies (such as the carbon dioxide taxes), appears to be crucial for increasing farmers' willingness to make long-term investments in willow plantations. This may be of extra importance in the case of those willow vegetation filters, which need additional investments. New environmental subsidies might be required within CAP, linked to specific environmental services provided by multifunctional willow plantations.

5.3. Structural incentives and barriers

According to Rosenqvist et al. [22] the willingness to grow willow is influenced by factors such as geographical location, the age of the farmer, farm size and farm type.

Willow growers normally have larger farms and are often more focused on cereal and food crop production, compared to "non-willow" farmers. Thus, structural barriers against willow production appear to be lowest in areas dominated by large farms and cereal production. Such areas normally also have the highest demand for environmental services, such as eutrophication management (buffer strips) and treatment of polluted drainage water (vegetation filters).

5.4. Technical and geographical incentives and barriers

The local and regional conditions affect the possibilities to implement willow vegetation filters in different ways. The prospects for irrigation of willow plantations with municipal wastewater is determined by factors such as (i) whether the sewage plant has already invested in conventional technology for extended nitrogen treatment; (ii) the size of the municipality and location of the treatment plant, where increased size leads to increased costs for vegetation filters due to longer load pipes; and (iii) the amount of available farmland for willow plantations in the vicinity of the sewage plant [4]. The prospects for irrigation of willow plantations with drainage water is determined by factors such as (i) whether the farmland has drainage systems; (ii) drainage system design and age and (iii) also soil type, where sandy soils are more suitable for irrigation than clay soils. The prospects for willow plantation cultivation in the form of buffer strips are determined by the abundance of open streams in the landscape. It also depends on whether the farmland has drainage systems, but, contrary to the drainage water irrigation case, abundant drainage reduces the attractiveness of buffer strips.

The regional conditions for willow vegetation filters are also affected by the demand for biomass. The need for environmental services, such as reduced emissions of nitrogen to waters, is normally highest in the more densely populated regions of Sweden, which is predominantly farmland. This corresponds fairly well with good conditions for large-scale willow production, high biomass demand (e.g., for district heating), and limited competition from other biomass resources, such as logging residues from forestry [4,23]. In some less densely populated regions predominantly forested, a surplus of forest fuels may be a barrier to willow filters, but, at the same time, the problems of polluted wastewaters are normally significantly lower in such regions.

One potential risk concerning municipal wastewater treatment in willow vegetation filters is the transmission of potential human pathogens to recipient waters. Today, knowledge about such risks is limited, and more investigations are needed to facilitate more reliable risk predictions and guidelines concerning aspects of spreading pathogens [24]. A survey of the existing international literature indicates no clear evidence of disease transmission connected to municipal wastewater and sludge treatment in vegetation filters in general. However, this may not be due to the absence of disease, but rather to the absence of trustworthy epidemiological studies [25]. Nevertheless, some recommendations can be made, based on the results of a few recent studies in Sweden in which the pathogen transmission aspects of wastewater treatment in willow vegetation filters have been analysed [26–28]. For example, municipal wastewater irrigation should be avoided on structured soils (e.g., clay soils) and in groundwater recharge areas where the groundwater is used for human consumption (risk of transport of viruses in macropores down to the groundwater). Pre-treatment of wastewater is also recommended, since this significantly reduces the occurrence of pathogenic microorganisms (e.g., pre-sedimentation and a biological treatment step). The limited knowledge surrounding the aspects of pathogen transmission is a potential barrier against the establishment of willow vegetation filters, since local or regional authorities may require more reliable risk predictions before permissions are granted. However, knowledge concerning pathogen transmission aspects of conventional treatment methods is also limited today. The potential pathogen spreading risks associated with municipal wastewater treatment in willow vegetation filters need to be compared to the potential risks associated with current conventional treatment technologies within a systems perspective. Such a comparison may show that vegetation filters can lead to either reduced or increased risk, depending on local conditions.

5.5. The "Enköping model"

The "Enköping model" is a concept based on the experience gained in the city of Enköping, where three different actors (one farmer and the operators of the municipal sewage plant and of the heat and power plant) have developed mutual agreements concerning the establishment and management of a willow vegetation filter system for municipal wastewater treatment [20]. Enköping is a city in central Sweden with about 20,000 inhabitants. It is located in a densely populated region where several cities have district-heating systems that utilise biomass. Enköping has a district-heating plant for combined heat and power production, which has used various types of biomass (mainly logging residues) since the 1980s. Owing to the projected increase in biomass use, the availability of forest fuels in the region may not be sufficient to meet the regional biomass demand in the future. Thus, from the perspective of the heat and power plant operators, the establishment of willow plantations in the close vicinity was seen as a welcome complement to the forest fuel resource base. At the same time, the larger sewage plants in the region have been obligated by regional authorities to halve their nitrogen emissions to water bodies due to increased eutrophication problems. This had the consequence that the sewage plant operators in Enköping needed to find a cost-efficient treatment method to reduce nitrogen discharges.

The 80-ha willow vegetation filter in Enköping was established in the year 2000 on farmland close to the sewage plant. The farmer involved financed the willow plantation costs, whereas the sewage plant operator paid for the irrigation systems (drip irrigation) and the 3-ha large storage dams where the wastewater is stored during the winter. The agreement between the sewage plant operator and the farmer consists of a long-term contract (12 years) whereby the sewage plant operator is allowed to irrigate the willow plantation with wastewater and apply sewage sludge. The sewage plant pays the farmer an annual compensation for this utilisation of the willow plantation. The sewage plant operator is responsible for the irrigation systems (including the investment and maintenance cost for the drip irrigation system and the storage dams). The farmer, on the other hand, is responsible for the willow plantation (including establishment, cultivation and harvesting costs).

The agreement between the farmer and the heat and power plant operator consists of a contract by which the heat and power plant operator is obligated to buy the harvested willow at the current market price. Also, the heat and power plant operator is allowed to recycle the wood ash back to the plantation. The farmer is expected to sell the willow harvest to the heat and power plant. In practice, the harvest operations are carried out by a bioenergy company specialised in willow production. The agreement between the operators of the heat and power plant and the sewage plant does not consist of a formal contract, but rather of a mutual understanding of how to utilise the willow vegetation filter in an optimum way (e.g., suitable time for harvest, suitable combination of wastewater, sewage sludge and wood ash applied to the plantation).

Several factors have been identified as crucial for the success of the "Enköping model" (Fig. 2). First, the operators of the sewage plant and the heat and power plant, as well as the farmer, have been proactive and open to new solutions. Second, advisors from a willow producing company (in this case Agrobränsle AB) have actively supported the various actors and increased their knowledge about willow vegetation filters, and thereby functioned as a "catalyst" in the process. Third, the local and regional authorities have been positive and interested in testing new wastewater treatment solutions. The mutual agreements have divided the various risks involved among the three actors. The main risk for the farmer is the production risk (e.g., reduced yields due to diseases, weeds etc). The main risk for the sewage plant is the treatment efficiency risk (e.g., reduced treatment efficiency due to technical problems in the irrigation system, etc.). The main risk for the heat and power plant is the demand risk. This distribution of risks among the actors involved in the willow vegetation

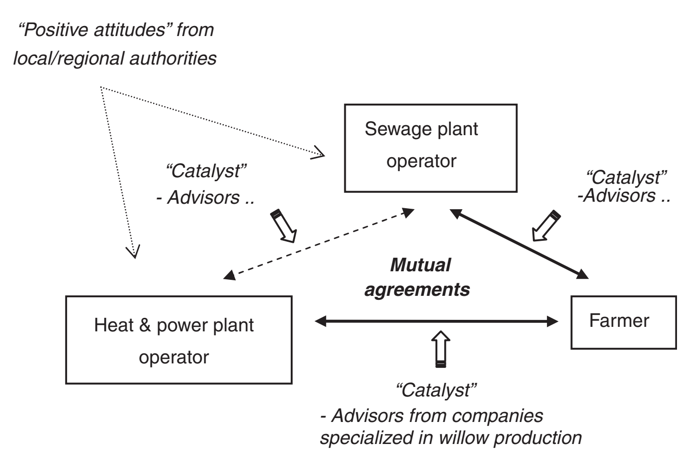

Fig. 2. Illustration of the "Enköping model" (see text for a more detailed explanation).

filter application has probably contributed to the success in Enköping.

6. Conclusions

Some of the data used and technology assumptions made in the calculations presented in this paper are uncertain. However, despite these unknowns, the results obtained clearly show that the treatment of polluted wastewater in willow vegetation filters is an attractive concept from the economic, energy and environmental points of view. In willow vegetation filters, plant nutrients are recycled and utilised in an efficient way for the production of renewable energy in the form of biomass, instead of being wasted or causing eutrophication. For example, if the annual Swedish per capita, municipal wastewater load were treated in willow vegetation filters, the biomass produced would be sufficient to meet approximately half the annual Swedish per capita, space heating demand (supplied by district heating systems).

Despite the various benefits of willow vegetation filters, several potential barriers exist against their large-scale implementation. Some of these are due to lack of knowledge, such as regarding the risk of the spread of pathogens: On this, more research is required. Others concern to the allocation of benefits and risks among the actors involved. However, several barriers are due to current policies within the agricultural, energy and environmental fields, and lack of harmonisation among theses policies. Thus, information about the concept and improved knowledge among authorities and policy makers seem to be crucial to achieve an increased implementation in the future.

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