Willows for energy and phytoremediation in Sweden

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Short-rotation willow coppice is cultivated not only to produce biomass for energy, but also to treat waste products, taking up pollutants from soil and water.

Short-rotation willow coppice is cultivated in Sweden to produce biomass for energy. The crop is commercially grown, mainly on agricultural land, and the biomass produced is used in district heating plants for combined heat and power production.

In recent years, nutrient-rich waste products – mainly urban wastewater, landfill leachate, industrial wastewaters (e.g. log-yard runoff), sewage sludge and wood-ash – have been successfully applied to the willow coppice to reduce, through plant uptake, the content of pollutants and/or excess nutrients in water and soils, and to facilitate microbial degradation of organic pollutants. This process is known as phytoremediation.

The benefits of such practices are both environmental and economic: this method of treating waste products (which here can be considered more as resources than as wastes) is more cost effective than conventional treatments, and the nutrients contained in the waste products serve as low-cost fertilizers to increase biomass production. This article provides an overview and examples of the use of short-rotation willow coppice in phytoremediation systems for treating different kinds of waste in Sweden.

WILLOW CULTIVATION FOR BIOMASS PRODUCTION

Cultivation of short-rotation willow coppice was introduced in Sweden after the oil crisis in the 1970s, with the intention of replacing fossil fuels by new energy sources. Extensive research to identify fast-growing species that could be grown intensively for use in energy production suggested that willows grown in coppice systems were the most suitable (Sirén, Sennerby-Forsse and Ledin, 1987). Nutrient utilization and stand management were seen to be more cost efficient for willow than for other woody species, and short-rotation willow coppice proved to be a sustainable way of producing fuels that were carbon dioxide neutral, since burning of the biomass would release into the atmosphere the carbon dioxide that the plants had taken from the air.

About 16 000 ha of willows in short-rotation coppice systems are currently grown in Sweden, consisting mainly of different clones and hybrids of *Salix viminalis*, *S. dasyclados* and *S. schwerinii*.

Willow cultivation is fully mechanized from planting to harvest. In the initial phase, approximately 15 000 cuttings per hectare are planted in double rows, to facilitate future weeding, fertilization and harvesting. Conventional inorganic fertilizers have commonly been applied in the years following planting. The willows are harvested every three to five years, during winter when the soil is frozen, using specially designed machines. The above-ground biomass is chipped on-site, then stored or directly burned in combined heat and power plants.

After harvest, the plants coppice vigorously, and replanting is therefore not necessary. The estimated economic lifespan of a short-rotation willow coppice stand is 20 to 25 years.

Today, biomass production of willow grown commercially in Sweden is about 6 to 12 tonnes per hectare per year, depending strongly on site conditions.

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EXAMPLES OF LARGE-SCALE PHYTOREMEDIATION SYSTEMS IN SWEDEN

Urban wastewater

Urban wastewater contains nitrogen and phosphorus and is in most cases a well-balanced nutrient solution that can be used for fertilizing plants. For sanitary reasons, however, it is only suitable for use on non-food, non-fodder crops, such as short-rotation willow coppice.

During the 1990s, large willow plantations equipped with drip or sprinkler irrigation systems were established adjacent to wastewater treatment plants to improve the efficiency of nitrogen treatment while producing biomass irrigated with wastewater. It was assumed that if biomass production were 10 tonnes of dry matter per hectare and the nitrogen concentration in the willow shoots 0.5 percent, then 50 kg of nitrogen per hectare would be removed from the field at harvest each year. Research has shown, however, that nitrogen retention in short-rotation willow coppice can be more than 200 kg of nitrogen per hectare per year because of denitrification (the microbial transformation of nitrate to nitrogen gas) and long-term build-up of nitrogen in the soil (Aronsson and Perttu, 2001).

In Enköping, a town of about 20 000 inhabitants in central Sweden, a novel system has been introduced. The nitrogen-rich wastewater from dewatering of sludge, which formerly was treated in the wastewater plant, is now distributed to an adjacent 75-ha willow plantation during the growing season. This water contains approximately 800 mg of nitrogen per litre and accounts for about 25 percent of the total nitrogen treated in the wastewater treatment plant. The water is pumped into lined storage ponds during the winter and used for irrigating short-rotation willow coppice during the summer (May to September). The system was designed so that conventionally treated wastewater can be added to promote plant growth. The willows are irrigated for about 120 days annually.

The system treats about 11 tonnes of nitrogen and 0.2 tonnes of phosphorus per year in an irrigation volume of 200 000 m^3 of wastewater, of which 20 000 m^3 is water derived from dewatering of sludge after sedimentation and centrifugation. Irrigation ceases automatically on rainy days. Irrigation rates reach a daily mean value of about 2.5 mm during the growing season.

Possible environmental hazards associated with such applications, e.g. nitrogen leaching and nitrous oxide (N_2O) emissions into the atmosphere, are monitored; the results so far indicate minimal risks after wastewater application.

Landfill leachate

Landfill leachate (water that has percolated through landfills) is usually treated together with urban wastewater in wastewater treatment plants. This is generally costly and involves high energy consumption because the leachate must be transferred away from the site for treatment. Therefore, landfill operators are becoming increasingly interested in alternative solutions for on-site treatment of leachate. One method is to aerate it and then use it to irrigate short-rotation willow coppice, either on restored parts of the landfills or on adjacent arable fields. The objective is to sustain plant growth and minimize the potentially


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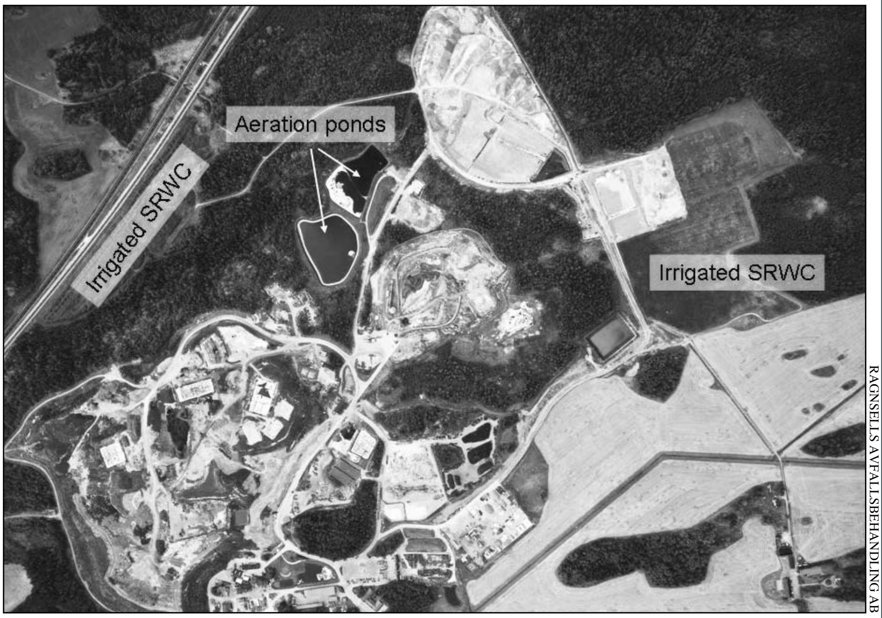
The 75-ha willow phytoremediation system at Enköping, central Sweden: wastewater treatment plant (foreground), ponds for winter storage of wastewater (background) and willow fields irrigated by wastewater from sludge



Aerial view of the landfill at Högbytorp, central Sweden, operated by Ragnsells Avfallsbehandling AB: landfill leachate is aerated in aeration ponds and used to irrigate adjacent willow coppice fields in summer

negative effects of the usually high ionic strength of landfill leachate, which often has chloride concentrations in the order of 1 000 mg per litre. The main advantage of this method is the low establishment costs compared with conventional on-site, engineered systems.

A willow plantation established to restore a landfill decreases leachate formation by means of high evapotranspiration. A near-zero net discharge of landfill leachate can be achieved by recycling this wastewater into a short-rotation willow coppice plantation, even in the humid climatic conditions of northern Europe. Simultaneously, hazardous compounds in the leachate (e.g. ammonium and a range of persistent and potentially toxic organic substances) are taken up by the willows or retained in the soil-plant system. A high concentration of ammonium ions in water is an environmental hazard, but if it is carefully monitored, ammonium can also be considered a source of nitrogen for the willow plants.

There are currently about 20 sites in Sweden where landfill leachate is used to irrigate short-rotation willow coppice in sprinkler or drip irrigation systems. For example, at Högbytorp in central Sweden, a system operated by the company Ragnsells Avfallsbehandling AB stores and aerates the landfill leachate in ponds and then pumps it into a 5-ha short-rotation willow coppice field which is irrigated daily during the growing season with approximately 2 to 3 mm of wastewater.

Differences in leachate composition from various landfills under different soil and climatic conditions, as well as differences in uptake of chemicals by different willow clonal materials, need to be considered in the design and management of leachate treatment systems involving irrigation of short-rotation willow coppice.

Log-yard runoff

At sawmills and pulp mills in Sweden, stored wood is sprinkled with water in summer to protect it from damage by insects and fungi and from cracks that form when the wood dries out. The runoff water contains a range of organic compounds originating from the tree bark, as well as substantial amounts of phosphorus originating both from the bark and from soil particles attached to the logs or to the tyres of the trucks transporting the logs. A medium-sized sawmill in Sweden consumes approximately 100 000 m^3 of water annually for watering stored wood; therefore large amounts of runoff water need treatment. In addition, wastewater produced from the log-yards after rainfall or snow-melt can pollute neighbouring catchments or groundwater if it is not collected and treated. Until recently, in most cases such water has been disposed of in rivers or lakes.

The content of the wastewater varies depending on the wood material stored and the log-yard storage conditions. The main environmental problems are caused by phenolic acids, total organic carbon, heavy metals and increased phosphorus concentrations.

At the Heby sawmill in central Sweden, about 60 000 m^3 per year of log-yard runoff is recycled to a 1-ha short-rotation willow coppice field. The field is irrigated with sprinklers during the growing season at a rate of about 4 000 to 4 500 mm per year (33 to 38 mm per day for 120 irrigation days). This rate is very high compared with the amounts of urban wastewater and landfill leachate treated.

The runoff from the Heby sawmill has a relatively low hazard rating, with very low nitrogen concentrations, but it contains large amounts of organic compounds and phosphorus. Experiments have shown that after this water is applied to short-rotation willow coppice, the total organic carbon and phenolic compounds in the groundwater are decreased (although phenolic compounds do not appear to be a problem, owing to low initial concentrations) (Jonsson, 2004). Furthermore, neither the growth of the willows nor the adjacent water basins appear to be negatively affected by the high loads of phosphorus and total organic carbon. However,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A 1-ha willow coppice field in Heby, central Sweden, irrigated by log-yard runoff from an adjacent sawmill

the very high amounts of water used saturate the soil, which reduces growth of the willows. Reduction of the total irrigation volume to 10 to 20 mm per day was found to improve both plant vigour and the efficiency of nutrient uptake, since it entailed treatment over a longer period.

Sewage sludge and wood-ash

About 10 000 ha of short-rotation willow coppice in Sweden have been fertilized with sewage sludge. Sewage sludge is not a balanced fertilizer in terms of plant nutrients, since it contains some nitrogen (mainly organically bound) and high amounts of phosphorus but very little potassium. Therefore, mixtures of sludge and wood-ash are applied to willows when wood-ash is available. This more balanced fertilizer replaces conventional inorganic fertilization.

The idea is that the effects of hazardous heavy metals and phosphorus in sludge-ash mixtures should be minimized by plant uptake and retention in the soil-plant system. At harvest, shoot parts that contain heavy metals are removed from the system and burned, and this material is partly recycled by applying the ash to the willow coppice stands. Only bottom-ash (ash left at the bottom of the boiler) is applied, since it has a lower heavy-metal content than the fly-ash (ash precipitated in filters in the chimney).

The mixtures of sludge and ash are applied to the willow coppice stands during the establishment phase and after every harvest – in other words, every three to seven years – in order to compensate for the removal of nutrients by harvesting. In practice, the amount applied is equivalent to about 22 to 35 kg of phosphorus per hectare per year (Naturvårdsverket, 1994).

Heavy metals in the soil-plant system after application of sludge-ash mixtures are within the permitted limits, and total concentrations of cadmium, considered one of the most hazardous metals for human health, are reduced (Klang-Westin and Eriksson, 2003). When the biomass is burned, cadmium and other heavy metals will remain in the different ash fractions, and will need further attention in order not to be recycled back to arable land. It is technically relatively easy to remove heavy metals from ash, but since this environmental service is not paid for at present, ashes contaminated with heavy metals are usually put on landfills.

CONCLUSION

When used for phytoremediation, short-rotation willow coppice offers advantages such as high biomass yields and removal of hazardous compounds through frequent harvests. The high evapotranspiration rate and root tolerance of willows in flood conditions allow the use of high irrigation rates. In addition, short-rotation willow coppice stands are capable of cleaning polluted sites by taking up substantial amounts of heavy metals such as cadmium, and they can retain large amounts of nutrients in the soil-plant system. Short-rotation willow coppice phytoremediation systems successfully remove hazardous compounds contained in the various wastes in Sweden, and utilize the nutrients and water applied in the production of biomass. Large-scale systems provide ecologically sound and cheap alternative treatment solutions, while biomass production for energy purposes is increased. ◆

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