WILLOWS BEYOND WETLANDS: USES OF *SALIX* L. SPECIES FOR ENVIRONMENTAL PROJECTS

YULIA A. KUZOVKINA and MARTIN F. QUIGLEY*
Department of Horticulture and Crop Science, The Ohio State University, 2001 Fyffe Court, Columbus, OH 43210, U.S.A.
*(*author for correspondence, e-mail: mquigley@mail.ucf.edu, Tel: 407-823 3146, Fax: 407-823-3569)*

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Abstract. Species of *Salix* characterized by particular physiological adaptations and ecological resilience are predisposed to use in conservation and environmental projects in many climatic zones and adverse microsite conditions. The economic importance of *Salix* is currently increasing and emerging in a wide array of practical applications to restore damaged ecosystems. Here we describe the ecology, physiological characteristics and agricultural requirements of *Salix* and present an integrated picture based on literature review, of current uses for willows well beyond wetland and riparian situations. These uses include ecosystem restoration, phytoremediation (phytoextraction, phytodegradation, rhizofiltration and phytostabilization), bioengineering (water and wind erosion, and protective structures), and biomass production for both fuel and fiber.

Keywords: biofiltration, biological engineering, ecological restoration, erosion control, phytoremediation, *Salix*, willow

Introduction

The history of human use of willows predates stone-age technology. In northern Europe and the Pacific northwest of America, willows represented the most common structural component of wattle/daub construction for shelter and fencing. Flexible willow stems were also the primary material for basket production and straight willow branches were used for arrow shafts and fish traps. Indigenous peoples in North America and Eurasia used willow bark infusions as analgesics and for at least two centuries before the development of the synthetic production of aspirin, salicin extracted from *Salix* bark was commercially exploited.

More recently the uses for willows have increased, and the range of applications for willows is directed toward minimization of negative impacts and outputs of the constructed environment on local ecosystems. *Salix* has become increasingly used in environmental restoration work, providing a cost-effective material for stabilization and reclamation of disturbed landscapes, phytoremediation, both riparian and upland erosion control, and biomass production. Our objective is to describe the full scope of environmental projects involving *Salix* species, provide brief information about *Salix* diversity, its ecological requirements and physiological characteristics. We summarize and categorize the current applications based on available reports.

Finally, we discuss cultural requirements for successful plant establishment, and specific limitations of the genus that should be considered in planning for mitigation of negative impacts on the environment.

The Diversity of the Genus *Salix* and its Importance in Regional Floras

Belonging to the family *Salicaceae*, the genus *Salix* comprises about 450 species worldwide distributed mostly in the Northern Hemisphere (Argus, 1997). Although predominantly occurring in temperate and arctic zones, willows are also present in subtropical and tropical zones and include trees, shrubs and groundcovers. The geographical distribution of willows includes all continents except Antarctica and Australia.

The total number of willow species growing throughout North America is about 106 (Zomleter, 1994). In many northern floras the number of willow species outnumbers those of other woody genera (Figure 1). In temperate areas, a variety of native willow species is almost always available near the site of a rehabilitation project; these can provide site-specific naturalizing materials with wide public recognition and acceptance.

Ecology

Species of the genus *Salix* differ in their ecological distribution and can be divided into two major groups: alluvial or riparian (growing along rivers, streambanks and

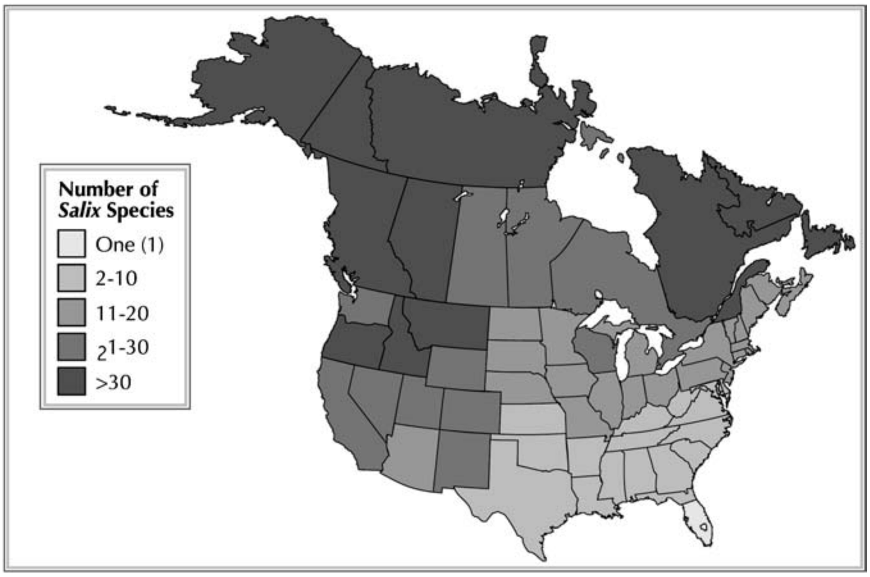

Figure 1. Salix species diversity in U.S.A. and Canada based on regional floras.

point bars) and wetland (growing on saturated soils). In both situations willows form relatively stable successional stages (Skvortsov, 1999; Kowalchik, 2001). While most *Salix* species are well adapted to hypoxic conditions, habitat characteristics suggest that some species have a preference for mineral rather than organic soil.

The autecology of willows also includes the strategy of early successional plants colonizing newly opened habitats, including upland areas. Those comprise man-made habitats such as roadside ditches, abandoned agricultural fields, railroads, old mine tailings, and gravel pits as well as recently burned, glaciated (soilless) or flooded areas (Argus, 1986; Skvortsov, 1999) where disturbance results in an open community with low competition levels, allowing a temporary increase in the dominance of opportunistic species.

The important adaptations and limitations of willows as pioneer species include their ability to colonize nutrient-limited oligotrophic sites such as bogs, sand dunes, river sand and gravel-bars; formation of symbiotic associations with mycorrhizal fungi which provide an additional supply of nutrients for plant growth (*Salix* species benefit from vesicular-arbuscular endomycorrhizae that utilize phosphorus, as well as ectomycorrhiza that use organic nitrogen (Schramm, 1966; Lodge, 1989; Heijden and Kuyper, 2003)); annual production of numerous seeds and an effective system of seed dispersal for long distance travel (light weight and hair attachment of willow seed), increasing the chances of finding an opening for germination and growth; establishment into vegetation gaps favoring those plants that can tolerate full sunlight (willows are not adapted to shade); and high relative growth rate with relatively short life expectancy (Raven, 1992).

Through different stages of development and growth, *Salix* species exhibit different moisture requirements. The common ecological restriction of *Salix* to wetlands and floodplains reflects an environment with constant moisture supply for immediate seed germination (Dorn, 1976). Moisture availability at the time of seed dispersal is critical because seeds of *Salix* are viable for only a few weeks (McLeod and McPherson, 1973; Maroder *et al.*, 2000); this can be a limiting factor in regions with dry conditions in late spring. However, after seedling establishment, constant soil moisture is not as important to survival of many willow species (Skvortsov, 1999). To summarize, the primary factors controlling the native distribution and abundance of species are the availability of moisture for seed germination and seedling establishment, an absence of early competitors, and availability of full sunlight.

Colonization of disturbed sites by *Salix* species can "anchor" a pioneer community, accelerating the recovery of damaged ecosystems and re-establishment of natural ecological complexity. Microclimate changes following the appearance of colonizing willows include an increase of surface shade, annual production of leaf debris, root action and formation of humus, thus improving the soil structure and nutrient status (Stott, 1992).

Physiological Characteristics

The essential physiological characteristics that affect *Salix* suitability for environmental restoration projects include:

- Superior growth and productivity even at juvenile stages; the highest capacity to convert solar radiation into chemical energy among woody plants under certain climatic conditions (Christersson *et al.*, 1993; Wilkinson, 1999).
- Extensive fibrous root system in the many shrub-type species, with the majority of fine-roots found in the upper 40–45 cm of the soil profile; continuous growth of fine roots from May through October (Gray and Sotir, 1996; Rytter and Hansson, 1996).
- High rates of evapotranspiration during the growing season (Persson and Lindroth, 1994; Lindroth *et al.*, 1995; Ledin, 1998; Ebbs *et al.*, 2003).
- Efficient uptake of nutrients (Ericsson, 1981; Elowson, 1999); high filtering capacity for nitrogen; ability to facilitate denitrification in the root zone (Aronsson and Perttu, 2001).
- Tolerance of flooded or saturated soils and oxygen shortage in the root zone (Jackson and Attwood, 1996; Krasny *et al.*, 1988; Aronsson and Perttu, 2001; Kuzovkina *et al.*, 2004a); some species are tolerant to increased concentration of carbon dioxide and methane (Maurice *et al.*, 1999).
- Ease of vegetative propagation due to preformed root primordia on the stems, and possibility of vegetative reproduction from horizontally lain willow rods (Carlson, 1950; Gray and Sotir, 1996).
- Vigorous re-establishment from coppiced stumps (Ceulemans *et al.*, 1996; Philippot, 1996).
- Ability to accumulate high levels of toxic metals, especially Cd (Klang-Westin and Eriksson, 2003).

In addition, all *Salix* species are well adapted to light and moderate fire regimes, resprouting from roots or root crowns; some willows are considered drought-tolerant, tolerant to deposition and resistant to moderate salinity (Kraebel, 1936; Mang and Reher, 1992; Gray and Sotir, 1996; Hightshoe, 1998; Kowalchik, 2001).

The perennial habit of willows confers advantages compared to annual plant species: larger amount of litter and increased humus content in the soil, efficiency of nutrient uptake over a longer growing season, better root penetration into the soil, and higher water use (Ledin, 1998).

While other early successional genera, particularly poplars, are used in similar environmental projects and posses many characteristics common with willows, many attributes of willows are superior. The number of *Salix* species is ten times greater that those of *Populus*, and their geographical distribution and physiognomic range present more diversity for exploiting the biological variation within the genus and consequently a greater range of environmental applications (Verwijst, 2001).

It has been shown that biomass production in willow plantations is higher than in poplar (Perttu, 1993). The fine fibrous root system of willows is more effective in erosion control than the large rope-like root system of some poplars (Wilkinson, 1999). Willows accumulation of Cd is higher than poplars (Robinson *et al.*, 2000).

Species of *Salix* characterized by particular physiological adaptations and ecological resilience are predisposed for use in conservation and environmental projects in many climatic zones and adverse microsite conditions. These include ecosystem restoration, phytoremediation, bioengineering, and biomass production.

Ecosystem Restoration

ECOLOGICAL RESTORATION OF WETLANDS AND WILDLIFE CONSERVATION

The important ecological role of *Salix* species relates to their affiliation with wetlands, for which restoration is a primary goal of numerous environmental projects. A significant disappearance of wetlands caused by agricultural and urban drainage has reduced native willow habitat in general, and the distribution of certain *Salix* species in particular. The importance of preservation of natural willow populations and ecosystems associated with them is currently emphasized (De Vries, 2001).

The current federal wetland policy of "no net loss," based on mitigation of damaged and destroyed natural sites with sites of equivalent ecological complexity is aimed at habitat replacement, enhancement of downstream surface water quality, and decreased risk of flooding (Mitsch *et al.*, 1998). Willow is an effective genus for ecological restoration of wetlands, in both structure and function and commonly installed in riparian restoration programs as a "nurse crop" for the establishment of larger and longer-lived woody species.

Willows have a high wildlife value, providing rich habitat and food for diverse organisms (Hightshoe, 1998; Sommerville, 1992). There is evidence for a rich insect fauna (up to 450 species) associated with willows (Kennedy and Southwood, 1984). Numerous invertebrate herbivores from aphids to caterpillars feed on willows, and support a large food-web of higher trophic level organisms. Many animals depend on willows for food (mostly leaf, stem and bud tissue) and shelter; willows provide browse for deer, elk, moose and livestock, caribou, muskrats, porcupines and willow wood is a preferred food and building material for beavers (Smith *et al.*, 1978). Willow stands support a high density of breeding bird communities and wetland willow thickets provide stopover sites for about sixty bird species, the highest number for all studied habitats (Bates, 1951). Their overhanging crowns above streams supply cover, shade, and a source of food in the form of insects for fish. Opportunities for viewing moose as well as elk, deer, songbirds and waterfowl add to the recreational value of willow associations (Kowalchik, 2001).

LAND RECLAMATION

Fast stabilization of chemically degraded land surfaces and reestablishment of a biologically active soil surface can be achieved using *Salix* species, which possess the major requirements for plant survival in environmentally disrupted areas: acid, wetness and, for some species, drought tolerance (Logan, 1992), low nutrient requirements for many species, and an ability to bud, root, and resprout from totipotent cells at even very old nodal areas. *Salix* species are able to establish on waste grounds and badly degraded soils with scarce topsoil, such as industrial spoils, mines and gravel pits, spoil-heaps of lignite mines, overburdens, quarries, highly eroded soils, waste sites and roadsides (Hartwright, 1960; FAO, 1979; White, 1992; Bungart and Huttl, 2001).

Tolerance of soil chemical contamination is an important requirement for survival in many situations and *Salix* potential for reclamation can be emphasized by the fact that, of the seven most important metal contaminants in soil, *Salix* has been reported to have tolerance to at least four (cadmium, copper, zinc, lead) and to one (cesium) of four radionuclides (Eltrop *et al.*, 1991; Sennerby-Forsse *et al.*, 1993; Punshon and Dickinson, 1997).

Willows will colonize open areas naturally (Schramm, 1966; Clewell, 1999), but as with other natural processes this early succession is spatially random and temporally unpredictable. With strategic planting of willows into disrupted landscapes and some assistance at early stages, restoration is achieved more quickly. For rapid establishment of plant cover willows can be used in the forms of mats, stakes, rooted cuttings and stumps with root masses. Low cost plantings of *Salix* and facilitation of the processes of land rehabilitation by altering microclimate, reducing runoff, providing ecologically diverse wildlife habitats and enhancing human recreational areas comply with new reclamation laws in many states and growing public concerns over wasteland management.

AFFORESTATION OF INDUSTRIAL SITES

Both active and abandoned industrial sites are characterized by increased concentration of air (nitrogen oxides, sulfur dioxide, hydrocarbons, ozone) and soil pollutants. Though information on *Salix* response to air pollutants is very limited and biochemical mechanism of its resistance remains unknown, there is some evidence supporting its suitability for planting around industrial sites. Zvereva *et al.* (1997) report that willows, along with birches, are the only woody species found in those industrial areas of Europe with very high air pollution levels. They concluded that long-term and severe pollution by sulfur dioxide and heavy metals suppressed growth of most woody species, but caused no measurable stress response in willows, and may even stimulate growth of leaves and shoots of *Salix borealis*.

Many authors cite *Salix* among other woody plants as tolerating urban conditions (Polunin, 1976; Schmidt, 1992). Resistance of some willow species to soil compaction and salinity (Hightshoe, 1992) can be exploited by its planting in urban naturalized areas bringing indigenous plant material into the urban environment.

Phytoremediation

Salix is currently under intensive research scrutiny for its potential for soil phytoremediation, the plants' ability to clean substrates through *chemical* and *metabolic* processes. Those include phytoextraction (the removal of heavy metals from soil due to the plants' uptake and translocation of metals into aboveground organs), phytodegradation (the accumulation and biochemical transformation of organic pollutants by plants and associated microorganisms), rhizofiltration and rhizostimulation (the removal of pollutants from aqueous solutions through direct uptake by plants roots) and phytostabilization (substrate dehydration and prevention of pollutant transport). Willows satisfy most of the requirements for plants used in phytoremediation: fast-growing, easily propagated, with extensive root systems, and ability to accumulate target pollutants. The ability of *Salix* to resprout after harvesting of aboveground biomass, along with potential production of energy biomass, makes it a suitable group of plants for phytoremediation purposes.

PHYTOEXTRACTION

Resistance of willows to some metals (Cd, Cu, Zn, Ni, Pb, Fe) and its ability to accumulate significant amounts of metal in plant tissues had been documented and suggested its possible use for metal extraction (Punshon and Dickinson, 1997; Ali *et al.*, 1999; Watson *et al.*, 2003; Ali et al, 2003; Keller *et al.*, 2003; Kuzovkina *et al.*, 2004b). The studies show much promise for decontamination of cadmium (Dickinson *et al.*, 1994; Landberg and Greger, 1994; Greger and Landberg, 1999; Robinson *et al.*, 2000; Klang-Westin and Perttu, 2002). While *Salix* should be defined as high accumulator of metal rather than a more efficient hyperaccumulator as are a few herbaceous plants, there is an essential advantage of *Salix* over herbaceous species for use in phytoextraction. Herbaceous hyperaccumulators have shallow root systems, but willows are recommended for deeper soil contamination. A combination of high metal concentrations in tissues, extensive root system, perennial habit and high biomass results in high potential for removal of significant amounts of Cd at stem harvest (about 2.6–16.5 g Cd ha^{-1} $year^{-1}$) (Keller *et al.*, 2003; Klang-Westin and Eriksson, 2003; Lunackova *et al.*, 2003). Profitable biomass production is an additional advantage of *Salix* over the herbaceous species, providing the farmer with an additional income during the restoration time (Eriksson and Ledin, 1999).

Although resistance to heavy metals has been well documented for *Salix*, biochemical mechanisms for metal tolerance is yet to be investigated. Some evidence indicates that metal tolerance in *Salix* may be attributed to phytochelatin synthesis (Ali *et al.*, 2003). Different species of willow, as well as some clones, vary considerably in their metal translocation patterns and their ultimate resistance to heavy metals (Riddell-Black, 1994; Pulford *et al.*, 2002). Inherited differences in lipid peroxidation and enzymes' level against high metal levels are a possible explanation for the metal tolerance of some clones (Landberg and Greger, 2002).

Phytoextraction with willows show promise for remediation and biofuel production of slightly contaminated sites and exhausted farmland (Perttu and Kowalik, 1997; Pulford *et al.*, 2002). Additional investigation is required to optimize metal uptake through clone selection and management measures (Eriksson and Ledin, 1999). Plant breeding programs are introducing new willow clones each year and an efficient screening technique to assess metal resistance is developing (Watson *et al.*, 2003). From an ecological perspective, potential adverse effects on ecosystem development should be carefully considered as metal contamination of vegetation could injure herbivorous organisms that consume willows (Mertens *et al.*, 2001; Ohlson and Staaland, 2001; Granel *et al.*, 2002).

PHYTODEGRADATION

While the ability of poplars to remove a large array of organic contaminants by absorption into plant roots is well documented, new evidence shows a favorable impact of willows on the fate of organic pollutants. Prairie Cascade willow (*Salix* x'Prairie Cascade') has shown vigorous growth on blackened soil produced by an oil spill and capability of cleaning the soil via stimulation of oil-degrading microbes associated with their roots (Thompson, 1998).

Willows have been recommended for recultivation of oil-mining areas in the Siberian taiga. Willow stakes planted in degraded areas without soil amendment quickly formed green cover, accelerating the disappearance of chemicals compared to bare land plots. Faster sequestration of pollutants than in previous attempts, when herbaceous plants were seeded on an expensively imported layer of soil, had been recorded (Chralovich, 2000). There is evidence that a significant decrease of 57% in mineral oil concentration in the plots planted with willow as opposed to 15% on fallow plots, took place on disposal sites for dredged sediment (Vervaeke *et al.*, 2003). Willows' ability to transport oxygen down to the root zone through aerenchyma formation may contribute to providing better conditions for bacterial growth. A study of planting of willows on landfill (Maurice *et al.*, 1999) has shown that those sites have higher methane oxidation rates compared to plots without trees. Trees with their extensive root systems may provide a better environment for methane oxidizing bacteria thus lowing its emission into the atmosphere.

Promising results in remediation of shallow aquifer sites contaminated with ethanol-blended gasoline spills using willow and its tolerance to increased levels of ethanol, has been reported (Corseuil and Moreno, 2001). In a laboratory experiment, cuttings of weeping willow (*Salix babylonica*) were able to reduce ethanol and benzene concentration in aqueous solution by more than 99% in less than a week through root uptake and sorption to plant biomass. It was suggested that uptake was significantly related to the plant's transpiration.

Willows show possible utility for the remediation of sites contaminated with cyanide compounds. Transport and metabolism of cyanide and ferrocyanide by willow has contributed to the degradation of these contaminants in the wastewater from gold mining (Ebbs *et al.*, 2003). While many plant species produce cyanide (mainly in the form of glycosides) for chemical defense and plant cells in general have a high capacity to eliminate free cyanide, there is some evidence that willow roots and leaves have the fastest rates of cyanide removal (Larsen *et al.*, 2004). Superior growth and biomass production and efficient hydraulic control of soil water levels due to high rates of evapotranspiration makes willow suitable as a potential "bioreactor" for cyanide removal.

RHIZOFILTRATION AND RHIZOSTIMULATION

The idea of constructed wetlands functioning as purification plants for wastewater is gaining currency in North America and Eurasia. Vegetation filters or "recirculating wastewater gardens" based on a free flowing water system with submerged vegetated beds are known to facilitate nitrogen removal due to hydraulic mass flux across the root zone as a result of water uptake by macrophytes (Martin and Reddy, 1997).

Species of genus *Salix* commonly growing along streams and swamp areas have been proposed as essential elements for vegetation filters, from which planting led to a substantial reduction of the polluted load (Elowson and Christersson, 1994; Kirt, 1994; Obarska-Pempkowiak, 1994; Perttu and Kowalik, 1997; Rosenqvist *et al.*, 1997) and are considered as a potential remedy for improving quality of domestic, municipal wastewater and agricultural runoff.

Physiological characteristics of *Salix* such as high rates of evapotranspiration, efficient nutrient uptake, tolerance of flooded conditions, and high biomass productivity, are crucial for the use of willows for vegetation filters. High accumulation of metal in their roots compared with other macrophytes and algae (Ali *et al.*, 1999), the ability to transport oxygen down to the root zone through aerenchyma formation contributing to better conditions for bacterial growth, and harvestable biomass providing necessary lignin for composting operations add to the value of willows included into constructed wetlands.

PHYTOSTABILIZATION

Willows' ability to dry swampy soils is well known by farmers. Historical references have even mentioned that due to high rates of evapotranspiration (phreatophyte-type of vegetation), willows planted in areas affected by malaria were the most effective for drying up the earth (Going, 1903). The establishment of willow vegetative buffer zones or biocurtains, for capping landfills, sewage treatment plants, steelworks and waste dumps has been applied in phytostabilization projects that aim to control soil water (Craven, 1994; Hasselgren, 1994).

Two approaches to strategic planting of willows include positioning of willow stand around the contaminated area to intercept contaminated runoff and placement of willow plantations on top of a contaminated area to reduce water entering the landfill. The idea of growing energy forests on restored landfill caps is under investigation. Willows' resistance to soil compaction is important for planting on restored landfill caps. There is evidence that some species are tolerant of landfill gases (Maurice *et al.*, 1999). Landfill leachate can be applied to short-rotation tree forests for reduction of both leachate volume and nutrient content and favoring microbiological activity and plant growth (Nixon *et al.*, 2001).

Another example of phytostabilization through dehydration of moist substrates is applied to dewatering of sewage and dredging sludge. Afforestation of sludge fields using willows appears to be one of the best solutions for their dehydration and preventing the spread of associated pollutants, due to reduction of surface water percolating into the groundwater. Planting of *Salix* on municipal sewage deposits intensifies the nitrification processes and contaminants in the sludge apparently do not affect willow growth (Scheirlink *et al.*, 1996; Wielgosz, 2000). Extensive root systems and abundant litterfall improve soil structure, increase nutrient cycling, promote biotic communities and create a forest microclimate.

The technique called SALIMAT has been described for dewatering of sludge from the dredging of waterways that is characterized by impassable swampy terrain where traditional planting methods are impossible. In this technique, willow rods are rolled around a central tube, and unrolled by dragging them across a field of sludge with a crane; the willow rods plant themselves by sinking slightly into the sludge. A dense vegetative cover is established in a few months with relatively low cost, providing stabilization of the substrate (De Vos, 1994; Stott *et al.*, 1994;Vervaeke *et al.*, 2001).

Willows' ability to sequester heavy metals and other contaminants in their root systems, halting their circulation within the environment, can be of great practical use (Ettala, 1988). The dense root system, penetrating deep into the soil, high transpiration rates providing efficient control of soil water and high filtering capacity for pollutants, along with continuous growth of some species during the whole growing season, increase willows' metabolic potential and create an efficient dehydration plant while locking up the pollutants.

Biological Engineering

Salix has been traditionally used for biological engineering based on its ability to provide *mechanical* functions for water and wind soil erosion, as well as to form protective structures (windbreaks, shelters and living walls). Important attributes defining the suitability of willows for these projects include high rooting capacity, extensive root system, tolerance to flooding and deposition, high availability and habitat value.

WATER EROSION

Species of *Salix* are often planted to stabilize riverbanks, lakes, ponds, man-made drainages and channels that are subject to frequent flooding (Bache and MacAskill, 1984; Morgan and Rickson, 1995; Wu, 1995; McCreary and Tecklin, 2000; Lefkowitz, 2002). As well as providing the mechanical stabilization of slopes, a vegetation cover with a continuous mat of fibrous roots minimizes erosion of soil particles, thus decreasing the level of suspended solids in adjacent waterways while providing better habitat for microorganisms that participate in purification processes. Many *Salix* species that are tolerant of flooding and coastal winds were found to be an efficient protection against wave erosion in reservoirs, stabilizing and naturalizong areas of bare mud (Polunin, 1976; Morgan and Rickson, 1995). Willows are also efficient in maintaining a secure upland slope by depleting soil moisture via transpiration (Gray and Leiser, 1982). Seepage areas can be controlled by willow wattling or brush layering, drying those areas and promoting stabilization.

Willows, along with poplars, play a major role in erosion control in New Zealand where transformation of forests into grassland coupled with burning and overgrazing caused increased runoff and accelerated erosion on steep and erodible slopes of hill country. Because of the grazing problem, the ability of willow establishment from large unrooted poles with plastic protectors and regeneration form stumps is advantageous (Wilkinson, 1999).

Techniques for erosion control with willows include the insertion of woody stems into the moist ground, or the horizontal application of stems and woven mats, protected from rolling down the slope by vertical stakes as well as willow bundles laid in shallow trenches and covered with soil. New cultivars with improved performance are chosen for bioengineering work (such as *Salix purpurea* 'Streamco' selected by the USDA for stabilization of streambanks (Gray and Sotir, 1996)).

WIND EROSION

Stabilization of sand dunes and other unstable surfaces can be achieved by planting tolerant *Salix* species (Schiechtl, 1980). In Germany willows are used for erosion control on sand hills along highways (Schiffer, 1999). Some willow species (*Salix humilis*, *S. myricoides*) survive in critical conditions of harsh wind, poor nutrient levels, low soil moisture content and constantly moving sandy ground (Cowles, 1991).

Construction of willow wattle screens is used to control the erosion of unstable mountain slopes in Eurasia (FAO, 1979) and *Salix* species are also recommended for controlling wind erosion on the peat soils with high groundwater tables (Morgan, 1995).

WINDBREAKS, LIVING WALLS AND SHELTERS

Fast growing species of willows create efficient and attractive windbreaks that protect agricultural lands, provide shade and shelter for livestock and enhance the view of vast landscapes along highways. Willow windbreaks are also effective shelterbelts for trapping snow while protecting roads and buildings from snow drifts (Bache and MacAskill, 1984). Living willow walls are becoming popular along highway noise retention concrete walls (Szczukowski *et al.*, 1998) and living willow hedges can be used to build robust soil-filled walls (Danks, 2002), in both cases enhancing the environment while suppressing noise, dust and exhaust fumes. The design of combined food and energy systems that include willow windbreaks for energy production in addition to food and fodder crops is under investigation (Foereid *et al.*, 2002).

Willow windbreaks can be established quite cost effectively by inserting 1-year old, 2 m long whips to a depth of 30–40 cm into a cultivated strip of soil. In 2–3 years, spaced 30 cm apart, willows will establish an effective windbreak 3–4 m tall, that in 2 years will reach 8 m (Stott, 1992). In more xeric conditions 3–6.5 m poles should be used so their bases reach the late summer water table (Kowalchik, 2001). Different species of *Salix* are suitable for this purpose depending on the desired height of the windbreak.

Willow hedges visually improve unattractive areas such as parking lots, rest areas or dumpster sites, where they can camouflage the undesirable view by providing a dense and rapidly growing screen. Willows offer great material for landscape architects in the emerging field of "ecological gardens" for government, corporate, and private clients designed to restore and enhance existing unappealing sites. Industrial buildings, stormwater detention ponds, and sewage sites can be turned into assets and mimic the natural plant communities promoting environmental sustainability. Willows are the least expensive woody plants, but provide a strong landscape image and instant visual impact to industrial parks (Bennett, 1999).

Biomass Production

The idea of utilizing biomass as energy source to replace fossil fuels, which are responsible for increased carbon dioxide loads in the atmosphere and contributing to global warming, is based on compensation of carbon dioxide uptake during plant growth production and its release during the burning of wood, representing carbon-neutral energy source. Willow appears to be among the most promising biomass fuels in many countries. Fast growth of willow can sequester more carbon than softwoods within a growing season (Lamlom and Savidge, 2003). *Salix viminalis* and *S. dasyclados* cultivated in Sweden for bioenergy produce up to 35 tons of stem per hectare per year under favorable conditions (Greger and Landberg, 1999) and *S. viminalis* is able to achieve the highest woody biomass production ever reported for Canada (Labrecque and Teodorescu, 2003).

Due to the adaptability of *Salix* to very extreme conditions and to nutrient poor and polluted soils, production of willow for biofuel may be feasible in "brown fields" and marginal lands (Dawson, 1992) though the contribution of willows harvested from polluted sites to atmospheric loading of contaminants needs to be investigated. Research on the use of willows for biomass plantations as alternative crops in soils contaminated with radioactive cesium has been conducted in Sweden and Belarus (Sennerby-Forsse *et al.*, 1993; Goor *et al.*, 2001; Vandenhove *et al.*, 2001) and found to be suitable for water-retentive soils. From the radiological and ecological perspectives energy production from willows was found to have potential, though with certain precautions for handling of wood and ashes. Use of excessive nutrients in wastewater as fertilizer for cultivation of biomass for energy purposes, or for compost, is under investigation. The levels of irrigation loading that provide an adequate supply of nutrients for plant growth and improve the quality of effluent leaving the plot have been determined, while domestic wastewater appears to be almost an ideal nutrient solution for *Salix* growth (Kowalik and Randerson, 1994; Perttu and Kowalik, 1997; Hasselgren, 1998; Hansson *et al.*, 1999; Aronsson and Perttu, 2001; Labrecque and Teodorescu, 2003).

Willow energy plantations create new habitat opportunities for wildlife due to increased complexity of the landscape, decreased cultivation intensity and use of pesticides, they have been proposed as an alternative to intensively managed farmlands in order to stop the impoverishment of farmland biodiversity in Europe (Sage, 1998; Berg, 2002).

Biofuel represents an ecologically promising energy resource for reducing greenhouse gas levels, acid rain, soil erosion, water pollution, and reduced dependence on fossil fuels. Additional economic benefits include reduced dependence on fossil fuels and improvement of rural economies; cultivation is not labor intensive and harvest takes place in winter when farm labor is available (Vandenhove *et al.*, 2001). National programs are developing in Canada and several countries within the European Community (Sweden, Denmark, Finland and the United Kingdom) that are designed to maximize productivity, to select new superior clones suitable for repeated harvesting and resistance to pests, and to develop management techniques for sustainable agriculture using willow. Numerous research projects have begun in the U.S.A. demonstrating the environmental benefits and sustainability of the willow biomass system from an energy perspective (Abrahamson *et al.*, 1998; Kopp *et al.*, 2001; Heller *et al.* 2003).

Culture Requirements and Limitations of the Genus *Salix*

Suitable agricultural methods for *Salix* establishment and the selection of species appropriate to specific sites in the landscape increase project success. Requirements for optimum establishment and viability of willow include: planting during the dormant period, provision of moist conditions at early stages of germination or rooting and full sun exposure. In propagation from the wild or from stock, mature willow logs, whips and cuttings can all be used (unrooted cuttings should be place in the ground before bud's break) and nursery stock with a well developed root system may be used especially in areas where weeds and drought are problems. One or two years of supplemental irrigation and weed control may be necessary during plant establishment while roots develop into an extensive system of surface lateral roots or reach the more permanently moist deep soil layers (Sage, 1999). A wide range of soils is suitable for plantings, and soil pH is less important in cultivation than in native habitats (Stott, 1992). Preformed root primordia are present on stem nodes in all species, except *S. caprea* and *S. scouleriana*, and ensure fast and inexpensive vegetative propagation.

The most common practice used for willow plantations in Europe is coppicing (pruning of all apical growth), based on the plants' ability to resprout very quickly after harvesting. Optimal harvest time is during the dormant season, which secures a root pool of nutrients for resprouting the following season (Sennerby-Forsse, 1994). The rotation cycle depends on species and growing conditions, and ranges from 3–5 years. Coppicing increases biomass, minimizes wind damage, enhances branching appearance of willows and supports a higher density of breeding birds (Wilson, 1992).

Although willows are quite easy to grow after they have been established, they may require some care. Periodic inspection and selective pruning are beneficial, especially after wind or ice damage. Damage caused by insects or disease can sometimes cause severe injuries to leaves and stems but rarely causes death of the plant. Proper siting of plants helps to increase their landscape value. Planted in shade, willows become leggy and unattractive, and more susceptible to diseases. It is important to consider that groupings of trees with shrubs of several species will look more natural and attractive than monospecific planting. Plants should be spaced far enough apart to allow them to reach mature size without overcrowding.

Constraints of *Salix* use in urban areas include potential for damage of drainage lines due to roots exploring for water, damage to foundations, or road and path base layers due to pressure exerted by roots when trees are planted too closely, and lack of ample space for growth of tree species. As with other fast growing pioneer species, *Salix* is "soft-wooded" and susceptible to breakage. Some species such as crack willow (*Salix fragilis*) and its hybrids have been proven to be invasive (Wilkinson, 1999) and should be avoided. Female plants of some species produce copious seed fluff (though not as much as cottonwood), so male specimens are preferred in urban applications (White, 1992).

Unfortunately, the commercial plant supply offers few native species. The misidentification of available plant selections due to taxonomical difficulties of the genus is a common problem in obtaining appropriate *Salix* species. While authors of many ecological projects include willows in their designs, in most cases they are listed as "*Salix* sp." without further specification. The full potential of the genus has to be explored at the species level with knowledge and understanding of their biology and ornamental features.

Though only a limited number of these clones have been tested, there is a wide variation within the genus regarding different characteristics and the pool of germplasm for selection and breeding is large (Ledin, 1996). Selection of species and clones with drought resistance, water-use efficiency, efficient nutrient uptake, high metal accumulation, radionuclide incorporation, pathogen and frost resistance, low palatability to herbivores, and having a long growth season to maximize benefits from evapotranspiration, are all important for breeding programs.

Conclusion

Salix represents a promising resource in mitigating impacts of environmental degradation. The versatility of the genus *Salix* for remediation in environmental projects is emphasized by the following fact that of 15 types of soil chemical degradation listed by Logan (1992), *Salix* offers remediation of 10 (erosion, mine spoil, industrial waste, dredge spoil, ore smelters, sewage sludge, petroleum spills, oil shale waste disposal, nuclear waste and landfills). Developing applications are designed to alleviate the major environmental pollutants: mineral nutrients, heavy metals and organic compounds addressing major environmental issues such as soil degradation, water eutrophication, habitat destruction and accumulation of greenhouse gases in the atmosphere.

Global and site-specific benefits can be achieved by building the links for nutrient and carbon circulation between cities and countryside, and by replacing some annual food crops with perennial energy crops (Börjesson, 1999). Multiple human values may be accommodated in a single planting of willow species. Remediation by willow plantations can clean or mitigate hazardous waste, stabilize and restore a site and produce wood for fuel. Willows planted as vegetation filters will facilitate excess nutrient uptake, reduce soil erosion, provide habitat for numerous organisms above and below the water level, and enhance a site's visual characteristics. During summer drought prunings from the sites of environmental projects can serve as supplementary fodder with nutritional value similar to that of lucerne/alfalfa hay (Wilkinson, 1999). Willow stems from a local energy forest can be used for building numerous living structures, serving as play elements and enhancing school and park environments; willows are also used for interdisciplinary research in creative environmental endeavors combining art, science and technology (Danks, 2002; Hunter, 1992). The integration of willow art into restoration projects – 'ecological art'– has received extensive public support and awareness and makes restoration projects entertaining for children (Lambert and Khosla, 2000; Lefkowitz, 2002).

To date, the most common environmental projects involving *Salix* are those associated with erosion control. However, national and international programs that include *Salix* for biomass production and phytoremediation are emerging. The pool of information on other applications of willows increases each year and it is expected that during the next decade rapid development of all aspects of willow cultivation will be experienced (USDA Forest Service, 2000; Verwijst, 2001). We hope that the focus on numerous current studies in this review will stimulate new development of site-specific solutions in anthropogenically modified landscapes, based on sustainable multifunctional and biocycling systems.

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