STRESS TOLERANCE AND HORTICULTURAL EVALUATION OF THE GENUS *SALIX*

DISSERTATION

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By

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ABSTRACT

The objectives of this study were to investigate the adaptability of the genus *Salix* to stressful conditions and to promulgate its ornamental potential. This research has focused on *Salix*'s tolerance of natural and anthropogenic stresses, including flooded soils, soil compaction, heavy metals, and ozone pollution; all are common conditions in urban environments. I found that neither soil compaction nor flooding caused a significant reduction in the growth of willows, but that anaerobic conditions rapidly triggered a wide range of morphological adaptations. The copper and cadmium uptake study, conducted in a greenhouse hydroponic system, revealed a general tolerance of willows of increased metal in the solution and the translocation of metal into plant aerial organs; copper appears to be more toxic to plants and less mobile than cadmium. The response of *Salix* species to acute ozone exposure was studied in a fumigation chamber and it revealed marked interspecific differences; both ozone-sensitive and ozone-tolerant species were documented. The ornamental qualities of cut branches from twenty species and cultivars of shrubby willows were evaluated and described in detail, focusing on those attributes, and phenological sequence, important for the floral industry. More than fifty promising willow species for alpine and small urban gardens were selected based on multi-year observations. Their names were taxonomically verified, and they are presented with detailed descriptions, horticultural uses and requirements, and details of provenance.

To Rick Eischen

For his tremendous support and shared interest in willows

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CHAPTER 1

INTRODUCTION

Belonging to the family *Salicaceae*, the genus *Salix* comprises about 450 species worldwide (Argus, 1997) with more than 200 known hybrids. Although predominantly occurring in temperate and arctic zones, willows are present in subtropical zone and include trees, shrubs and groundcovers. The geographical distribution of willows includes all continents except Australia.

The present research is dedicated to the physiological stress tolerance of *Salix*, its role in the constructed landscape, and its horticultural evaluation. Its goal is to study the genus *Salix* at the species level and to determine those characteristics that would promote *Salix* use in the landscape, as well as suitability for further research in both the horticultural and environmental arenas. The dissertation is comprised of original experimental research as well as the results of several years of observational studies in the field.

The experimental research is concerned with willows' tolerance of natural and anthropogenic stresses based on the whole organism. In Chapter 2, we studied the ability of *Salix* species to grow in compacted and flooded soils, and the effect of soil compaction and flooding on soil aeration.

For the efficacy of willow use in environmental phytoremediation, a series of experiments were conducted to investigate the ability of some North American native *Salix* species to tolerate and translocate heavy metals (Chapter 3). We also evaluated the sensitivity of an array of *Salix* species to acute ozone exposure, based on visible injury symptoms, and we assessed the temporal differences of damage throughout the growing season (Chapter 4).

The selection of species and cultivars of special horticultural merit comprised the field evaluation components of this research. Observational studies were conducted at the *Salix* collection of the Chadwick Arboretum at Ohio State University from 1999 through early 2003. The collection was established in 1999 for the purpose of horticultural evaluation, and as a hardiness and performance trial for *Salix* species in general, and included about 200 taxa introduced from the United Kingdom, Russia and Poland, in addition to an array of North American species.

The most promising species for alpine and small urban gardens, and those species with the potential for florist cut-stem production, were selected based on field observations of the Chadwick collection, and their taxonomical verification and species descriptions were compiled (Chapters 5 and 6). The publication of these horticultural evaluations will provide a greater awareness of the species for the industry.

The concluding chapter (7) presents an integrated picture of current applications and uses of willows in the green industries, with the main focus on the multiple opportunities that *Salix* can offer for ecological restoration projects, phytoremediation and bioengineering. This research has both basic and applied value, advancing knowledge in plant physiology while contributing to the landscape horticulture and nursery industries.

CHAPTER 2

EFFECTS OF SOIL COMPACTION AND FLOODING ON THE GROWTH OF 12 WILLOW (*SALIX* L.) SPECIES

Introduction

The soil environment is an important influence on both plant growth and function. Root growth depends on physical and chemical properties of the soil that can be significantly changed by compaction or flooding. Mechanical impedance, limited gas exchange between soil and the atmosphere and poor drainage are common problems associated with soil compaction (Craul, 1985). Compacted soil is a common problem in most urban settings (Quigley 2003, in review) and new construction sites, where the soil usually consists of mixture of very dense subsoil and construction fill and often presents a serious restriction to woody plant growth. Compaction occurs as a result of frequent foot and vehicular traffic during construction work, and intentional settling of the ground. Natural causes such as rainfall impact, soaking, loss of soil invertebrate community, and internal water tension (Glinski and Lipiec, 1990) can also result in compacted soil.

Flooded soils occur naturally around the world and represent another example of highly stressful root-zone conditions. The major constraint imposed by flooding is limited gas exchange. Diffusive resistance to gases, which is much greater in water than in air, usually causes a rapid drop of oxygen in inundated soils (Armstrong et al., 1994). The additional sinks of oxygen in waterlogged soils are the microbial and chemical oxygen demands that act as competitors with the root for the limited oxygen supply. High aqueous resistance to CO_2 and O_2 diffusion in submerging waters significantly affects plant survival, limiting the number of species able to survive for prolonged periods under such conditions.

The ability of plants to grow in compacted soil as well as to tolerate anaerobic conditions during inundation is reflected in numerous studies on many different plant genera. However, little previous research has been done on the ability of willows to tolerate soil compaction. Despite its affiliation with wetlands and riversides this genus, comprising about 450 species worldwide, has not been studied sufficiently for flooding adaptation. Previous work examined responses of *S. viminalis* to soil flooding and recorded the production of new aerenchymatous adventitious roots triggered by anaerobic conditions (Jackson and Attwood, 1996). The ability to form adventitious roots in response to inundation was studied in *S. interior* and *S. alaxensis* (Krasny et al., 1988) who concluded that it is correlated with to species' distribution on the floodplain.

The present research investigates effects of soil compaction and flooding on growth of 12 *Salix* species. The first objective of the experiment was to test the ability of *Salix* species to grow in compacted soil and under flooded conditions and to understand plant functioning in these different environments. We hypothesized that both compacted and flooded soils are characterized by limited gas diffusion and would inhibit root growth. The second objective was to study the effect of soil compaction and flooding on soil aeration and to determine whether these conditions affect plant growth or morphology.

Materials and methods

Both experiments were conducted in the OSU Howlett greenhouse (Columbus, OH) in June-August 2000 over eight weeks. Air temperature fluctuated between 20 and 27^{o}C, average relative humidity was 80% and light followed the changes of the natural environment. Plants for the experiment were set out in a randomized block design with four replicates. A block consisted of eight plastic units (24x35 cm) each containing 6 pots 13.5 cm deep with volume of 1250 ml. One replicate consisted of 48 pots, or treatments, involving two factors: 12 species and cultivars and four soil conditions (control, two levels of compaction, or flooding).

Twelve *Salix* taxa were used in the study: 7 native North American species (*Salix amygdaloides* Anderss., *S. cordata* Muhl., *S. discolor* Muhl., *S. eriocephala* Michx., *S. exigua* Nutt., *S. hastata* L., *S. nigra* Marsh.) and 5 Eurasian taxa (*S. alba* L.'Britzensis', *S. elaeagnos* Scop., *S. purpurea* L. represented by two cultivars 'Nana' and 'Streamco', and *S. repens* L.), representing systematically different sections of the genus *Salix*, as well as adaptation to different ecological conditions. Cuttings of N. American species were obtained from native habitats (in Ohio) and cuttings of introduced species were obtained from the collection at the Chadwick Arboretum (Ohio State University).

Softwood cuttings 8 cm long of *Salix* were rooted in small cells (volume 20 ml) in a misthouse for 2 weeks prior to the beginning of the experiment, to avoid stressing the plants during the initial phase of root formation. Root systems were well developed at the time of transplanting.

Field soil (Crosby Silt Loam, taken from the A horizon of Waterman Farm, Columbus) was used in the experiment. Soil was oven dried and weighed for the appropriate bulk density. The control treatment was soil packed into the cell without special efforts. The highest compacted level was represented by the maximum amount of soil that was possible to pack into the cells, using constant compressing of soil by hammering. The moderate compaction level contained intermediate amounts of soil between control and the high compacted treatments. For determination of soil bulk density at different compaction levels the appropriate amounts of oven dry soil were divided by the pot volume. The dry bulk density for control, moderate and the most compacted treatments was 1.05, 1.24 1.42 g ml^{-1} respectively. The pots prepared for flooded treatment contained soil amounts equal to the compaction control treatment.

Soil was pre-saturated and rooted cuttings with a small volume of soil were inserted into the pots (one plant per pot). Each unit was placed on a plastic tray and during the experiment the soil was watered from the bottom of the tray to avoid any alteration of compaction levels. Trays were filled with water once a day and fertilized each week with 100 mg l^{-1} N, 50 mg l^{-1} P_2O_5 and 100 mg l^{-1} K_2O. After 5 weeks growing in such conditions, the units for flooding treatments were placed into deep plastic containers filled with water. The water level in these containers was maintained 4 cm above the soil level for three weeks.

For all soil gas analyses plastic tubes 6 cm long (9 mm od, 6 mm id) with a rubber septum were placed into the soil of 48 pots (12 of each of four treatments) (Figure 2.1) and gas samples were taken once a week using 1-ml plastic disposable syringes. Oxygen, carbon dioxide and ethylene were measured using a Chrompack Capillary Gas Chromatograph, Model 436 (Packard, Downers Grove, IL, USA) at 150°C. For oxygen and carbon dioxide a thermal conductivity detector and for ethylene a flame ionization detector were used. Oxygen was analyzed on a 100x0.6 cm column of molecular sieve 5A and CO_2 was separated on a 50 x 0.6 cm Porapak T (Waters, Milford, MA, USA) column with helium carrier gas at 20 ml min^{-1}. Ethylene was separated on a 80-100 mesh alumina (Coast Engineering, Redondo Beach, CA, USA) column (50 x 0.6 cm), with nitrogen carrier gas at 60 ml min^{-1}. Soil air oxygen content was monitored once a week for 8 weeks. Analyses of carbon dioxide and ethylene were made during the final two weeks of the experiment.

At the end of the experiment all plants were harvested, material was separated into below and above the ground biomass, dried in the oven for 48 hours at 70° C and dry weights were recorded. Transverse hand-cut sections of roots 2 cm from the tip were desiccated, by a “critical point” technique. Sections were placed for 5 min. in 40% alcohol, 5 min. in 70%, 20 min. in 80%, overnight in 90%, 10 min. in 95%, followed by 1 hour in 100% of alcohol; the last step was repeated 3 times; then samples were carbon coated, and viewed under a scanning electron microscope under accelerated voltage 20keV.

Statistical Procedure

The data were analyzed statistically as two experiments: 1) control with two compaction levels and 2) control with flooding. All data were subjected to analysis of variance (SAS release 6.11, SAS Institute, Cary, N.C.) and the treatment effects reported were significant according to an F-test at the $\alpha = 0.05$ level.

For the results of gas analyses, the relationship between compaction levels, flooding and each of the gas concentration were subjected to analysis of variance using weeks as repeated measures for the gas exchange variables. Differences in below and above-ground biomass were examined by analysis of variance with untransformed data. Analyses were done separately for each species as well.

Results

Soil gas composition.

Throughout the compaction experiment the oxygen concentration did not fluctuate considerably in any treatment, remaining close to atmospheric level (Table 2.1). Statistically, the changes in oxygen concentration between compaction treatments were significant ($F_{2,68} = 3.34$, $p = 0.0372$) although the average concentration remained between 20-21% and it never dropped below 15%. The compaction treatments had elevated levels of carbon dioxide compared to control with the highest level (0.62%) in the heavily compacted soil ($F_{2,68}$=12.27 , p=0.001). Changes in ethylene concentration for compaction treatments were insignificant ($F_{2,68}$=0.56 , p= 0.576).

In contrast, a significant decrease of oxygen took place in flooded treatments with the average 9.11 % ($F_{1,45}$ =119.8 , p = 0.0001) (Table 2.2). The lowest oxygen concentration recorded for flooded treatments was 4.6%. The average carbon dioxide level found in the flooded treatment was 2.15%; the highest concentration, 4.82%. A significant increase of ethylene concentration took place in the flooded treatment compared to the control (average of 1.57$\mu l\ l^{-1}$ with the highest concentration value of 2.35 $\mu l\ l^{-1}$) ($F_{1,45}$ =221.42, p =0.0001).

Plant growth

Compacted and flooded conditions for all species were accompanied by continued growth of above ground biomass. Cuttings of all species had 100% survival in all treatments. No leaf abscission or any other decline or injury was recorded for any plant.

There was a significant interaction of species and treatment in both compaction ($F_{22,108}$= 3.67; p=0.0001 for below and $F_{22,108}$= 1.62; p=0.05 for above ground biomass) and flooding ($F_{11,72}$=4.87; p=0.0001 for below and $F_{11,72}$=3.56; p=0.0005 for above ground biomass) treatments (Table 2.3 and 2.4).

The higher level of bulk density in the compacted treatment was reflected in a significant change ($F_{2,108}$= 3.53; p=0.0327) of root growth. Two trends for root growth for 4 species with significant differences between treatments (Table 2.5) can be determined from the data: the highest root weight occurred in control for *S. amygdaloides* and in the medium or heavily compacted soil for *S. cordata*, *S. discolor* and *S. eriocephala* (Figure 2.2). There was no simple effect of compaction on above ground biomass. All species except *S. amygdaloides* showed no difference or better shoot growth in the moderate compaction treatment (*S. alba* and *S. discolor*) or in heavily compacted soils (*S. cordata*, *S. eriocephala*) (Figure 2.3). For species with significant changes of above ground biomass, these changes associated with below ground biomass: the higher root growth associated with the higher shoot growth at control treatment for *S. amygdaloides*, for medium compaction for *S. alba* and *S. cordata*, *S. eriocephala* in the highly compacted treatment.

There was no overall effect of flooding on above ($F_{1,72}$=0.03; p = 0.8609) and below ground biomass ($F_{1,72}$= 1.81; p = 0.183) (Table 2.4), though species responded differently to the treatment. Some species had a significantly higher below ground biomass in flooded soils (*S. alba*, *S. eriocephala*, *S. exigua*, *S. nigra*), while *S. amygdaloides* and *S. cordata* had lower root weight than in control treatments (Figure 2.4). For the rest of species the changes of root mass in flooded treatment were insignificant.

Significantly higher above ground biomass in flooded soil (Figure 2.5) was associated with higher below ground biomass for *S. alba* and *S. eriocephala*.

Salix cordata was exceptional in showing a considerable increase of shoot and root growth in compacted treatments, but a significant reduction of root growth under waterlogged conditions. This trend differs from the other species and needs some clarification through additional experiments.

Morphological changes

Within 3 days of flooding, hypertrophy of stem lenticels began to occur. Masses of white, callus-like cells developed on the submerged portions of the stems and 5-7 cm above water level in *S. alba*, *S. cordata*, *S. discolor*, *S. eriocephala*, *S. exigua* and *S. nigra*. Hypertrophy in *S. amygdaloides* had an unusual appearance with darker color and elongated shape (13-15 mm), consisting of loose parenchymatous cells (Figure 2.6). For the other species flooded lenticels remained round.

Significant proliferation of adventitious roots was observed in the upper 10 cm of flooded soil on submerged stems of those plants producing hypertrophied lenticels.

During harvesting, on some species we observed a certain proportion of straight thick roots (Figure 2.7), having spongy appearance in cross section. These roots emerged from the stem; had high porosity and few lateral rootlets. At the end of the experiment, thickened roots were found in *S. nigra*, *S. alba*, *S. exigua*, *S. discolor* and *S. eriocephala*. The roots of *S. nigra* and *S. alba* were thicker (diameter of 2-3 mm) than those of other species. Scanning electron microscopy of transverse sections of these roots revealed their aerenchymatous structure. The tissue structure was less open in *S. nigra* than in *S. exigua* (Figure 2.8, 2.9). Roots with aerenchymatous structure were not found in well-drained treatments.

Roots growing along the water surface ("snorkeling" or floating) were observed in *S. amygdaloides* (Figure 2.10). These roots extended for considerable length, up to 40 cm, from their point of origin and had numerous short lateral roots. These freely branched roots grow parallel to the water surface and floated just below water level exploring the upper aerobic layer.

After 4 days of flooding, *S. nigra* and *S. alba* started to develop dense masses of adventitious roots that grew upwards, reaching the surface of the water with root tips raised above water level (Figure 2.11, 2.12). By the end of experiment no morphological changes were recorded for *S. elaeagnos*, *S. hastata*, *S. purpurea* 'Nana', 'Streamco" and *S. repens*.

After the completion of the experiment the additional flooded trays not used at the experimental design, remained flooded for two more months. The plants remained healthy and continued to grow.

Discussion

<u>Soil atmosphere</u>

The hypothesis that poor soil aeration is the most important factor limiting root elongation in high bulk density soils was not confirmed. Soil is considered oxygen deficient at concentrations15% or less (Glinski and Lipiec, 1990). The biologically insignificant changes in oxygen concentration between compacted treatments and the control suggest that in spite of increased bulk density and therefore decreased soil porosity, oxygen exchange between soil and atmosphere continued to be efficient (average 20-21%) and even the lowest concentrations were sufficient for plant growth.

An increase of carbon dioxide along with the compaction can be attributed to decreasing macropore space with the compaction. Carbon dioxide in the soil produced by plant roots and microorganisms led to a three-fold increase concentration of CO_2 in the compaction treatments. Considering the low carbon dioxide concentration in the atmosphere, even changes less then 1% can be significant. The effect of such increase of carbon dioxide on root respiration is difficult to predict due to insufficient studies, and it probably varies with plant species (Glinski and Lipiec, 1990).

Mechanical soil impedance to plant growth is known to induce stress ethylene production by plant (Abeles et al., 1992), but no increased levels of ethylene were observed in any compaction treatment.

The flooded treatment represented a more profound gas exchange restriction. The alterations of all studied components of soil atmosphere were statistically significant. Oxygen and other gases diffuse in water about 10^4 times more slowly than in air (Armstrong, 1979), and oxygen depletion can occur rapidly due to respiration of soil microorganisms and plant roots in flooded soils. Low oxygen concentration (9.11%) during the experiment represents hypoxic conditions and can adversely affect plant growth.

It is known that accumulation of ethylene in soils as well as in roots occurs with waterlogging and that anaerobic atmosphere promotes production of stress ethylene in many plants (Abeles et al., 1992). The significant increase of ethylene that was observed in the flooded treatment confirms this concept.

Plant growth

The lack of significant decrease of above or below ground biomass in all treatments suggests the ability of many *Salix* species to function successfully under stressful sub-surface conditions. The roots of all species were able to grow even through the most compacted soil and penetrate the layers of soil all the way to the bottom of the pot. For many species both flooding and compaction appeared to be rather beneficial than detrimental to growth. Only *Salix amygdaloides* exhibited a certain retardation of root and shoot growth in compacted soil, as well as a reduction of root growth in flooded soil. Therefore, it was surprising that in flooded treatments there were no significant differences in shoot growth for this species. Probably even reduced root growth in flooded soil did not arrest shoot growth of the plants and no visible changes of vigor or plant mortality were recorded.

Morphological adaptations to flooding

The ability of plants to survive anaerobic conditions has been extensively studied with common crop plants such as maize, rice, soybean and pea, and in the majority of cases was related to production of morphological adaptations. It was suggested that species producing specialized stem and root architecture would have competitive advantages in flooded conditions because roots can thereby acquire additional oxygen.

The ability of willows to continue growth in hypoxic soil is consistent with their common habitat of floodplains with seasonal flooding and wetlands with permanently waterlogged soils. The number of *Salix* species used in the experiment revealed a wide range of adaptation: in 9 of 12 species studied, flooding stimulated the rapid production of distinct morphological changes. The role of ethylene, and possibly other compounds, in these morphological adaptations has been emphasized (Tang and Kozlowski, 1984; Abeles et al., 1992). The observed increase of ethylene production in flooded treatments during this experiment was probably responsible for triggering these adaptations.

A few strategies for obtaining additional oxygen were recorded for *Sali*x species through morphological adaptations triggered by flooding. They include root exploration of oxygen-rich upper water level (adventitious root formation, “snorkeling”or floating roots growing along the water surface), re-establishing root contact with the atmosphere (roots exhibiting negative gravitropism) and internal oxygen transport from the stem to roots (lenticel hypertrophy, formation of adventitious roots with aerenchyma). All of these adaptations facilitate gas supply to the anaerobic roots.

Production of hypertrophied lenticels is the result of intense localized phellogen activity in the stem, just below and above the water surface (Armstrong et al., 1994). The hypertrophies, or intumescences, consist of masses of cortical tissue with expanded and separated cells (Abeles et al., 1992) and result from cell wall degradation, extreme cell expansion and rapid cell division. Lenticels are more pervious to gas diffusion and therefore may enhance gas exchange.

The important role of hypertrophied lenticels is to provide the additional aeration to the stem and roots as well as to serve as openings for removal of toxic compounds produced as a result of anaerobiosis (Hook et al., 1970). Since the most important region for the oxygen entry into the stem through the bark is the basal region of the stem (Armstrong, 1968) hypertrophied lenticels are considered an effective and metabolically the least expensive way to react to changes of water table. There is evidence that ethylene is responsible for the hypertrophy of the stem-base, as well as of lenticels (Kawase, 1981).

Rapid production of adventitious roots in response to flooding provides an additional gas and solute absorption system for plant parts in the upper, well-aerated water layer. These may be the major roots providing water and nutrient supply to the plant during anaerobiosis and could serve as a replacement for roots damaged after exposure to anaerobic conditions. As a part of normal ontogenetic development, willows have preformed root primordial that are initiated on the stems during their first growing season and remain dormant as masses of undifferentiated cells in the inner bark (Carlson, 1950). The existence of root primordia in most species of *Salix* is very important for quick development of adventitious roots, enabling plants to re-adjust to rapidly changed conditions. Formation of adventitious roots is a more complex process than hypertrophy, and remains to be understood, but ethylene is probably involved in their formation (Armstrong et al., 1994).

The aerenchymatous tissue found in roots allows the efficient transfer of oxygen from the stem through an internal gaseous transport system to respiring root tissues. It is also is known that a surplus of oxygen can diffuse out of the roots, oxygenating the rhizosphere (Armstrong, 1964) and probably detoxifying certain compounds (Talbot and Etherington, 1987). Aerenchyma formation in adventitious roots is probably ethylene regulated (Jackson and Attwood, 1996). The unbranched structure of aerenchymatous roots allows them to penetrate into deeper layers of waterlogged soil and facilitate nutrient uptake.

As a result of reorientation of root growth under anaerobic conditions, a dense mass of upward growing (negatively gravitropic) adventitious roots can re-establish direct contact with the atmosphere and provide a constant source of oxygen. In this case diffusion of oxygen ocurs from the root apex toward its base. ABA is the most likely hormone responsible for changes in gravitropism under anaerobic conditions in other aquatic species (Summers and Jackson, 1994).

The long roots growing along the water surface observed with *S. amygdaloides* represent less common type of adventitious root formation for woody plants. These roots exploit oxygen present in the surface layer and this mechanism represents another effective way to provide the oxygen for plant respiration.

Relationship of morphological adaptations to flooding and plant growth

We observed a relationship between the capacity of some species to produce adventitious roots with aerenchyma or vertical roots, and their rates of growth. In the flooded treatment we saw a trend of increased below ground biomass of *S. alba*, *S. eriocephala*, *S. exigua* and *S. nigra*, compared with the control treatment. The same species were characterized by extensive production of thick aerenchymatous and vertical adventitious roots. We suggest that increase of below ground biomass can be attributed to the formation of these adventitious roots under anaerobic conditions. The species with increased root weight under the hypoxic conditions tended to produce higher above ground biomass as well.

For *S. amygdaloides* a decrease in below ground biomass took place, but it still formed adaptive structures such as hypertrophied lenticels, adventitious roots and “snorkeling” roots growing along the water surface. There was no decline of vigor in stems of this species. Possibly the decrease of root biomass resulted from reduced metabolic rate during anaerobic growth, as was suggested by Crawford (1992) for some wetland plant species.

Morphological adaptation is probably not the only soutce of flood tolerance; the internal gas transport that provides the oxygen for aerobic respiratory pathways may not be completely responsible for flood tolerance of Salix spp. Oxygen-deficient roots are often characterized by decreased water and nutrient uptake, leading to injury such as blackening of the lower leaves, petioles, and stem and leaf desiccation. The continued growth and lack of injury in species without visible morphological adaptation suggests that there may be other ways to compensate for anaerobic conditions.

The role of adventitious roots in flooded soils may be less important than is often thought and tolerance may be achieved without their production (Jackson and Attwood, 1996). The ATP required in anaerobic tissues is generated in glycolytic processes, mainly by ethanolic and lactic acid fermentation (Armstrong et al., 1994). For some species it is possible that pre-existing roots continued to service the shoots even under anaerobic conditions. In summary, the adaptation of *Salix* to growth in hypoxic conditions result from the combination of morphological, anatomical and metabolic adaptation. Specific metabolic adaptations of *Salix* species require future research.

<u>Ecological inferences</u>

The flood tolerance of willows is not based on a single morphological or physiological adaptation. The lack of a universal mechanism to tolerate unfavorable conditions is evidence of divergence between species throughout evolution. Species of the genus *Salix* differ in their ecological distribution. According to Skvortsov (1968) they divide into two groups: alluvial (growing along the rivers and smaller streams and requiring well aerated substrate) and non-alluvial (which can tolerate stagnant water). Habitat characteristics suggest that some species may have greater tolerance for poorly drained soil than others. According to the ecological observations of Skvortsov (1968) *S. alba* is typically an alluvial species. *Salix nigra*, *S. amygdaloides*, *S. exigua*, *S. eriocephala* also occur predominantly in riparian habitats characterized by well-aerated substrate (Argus, 1986), while *S. discolor* represent a non-riparian species which has less exacting requirements for soil aeration and is able to tolerate stagnant water.

We expected to see a differential response to flooding, corresponding to the autecology of species throughout the experiment. However, we observed that both ecological groups could develop morphological adaptations for aeration. Alluvial or riverside species exhibited a wider range of such adaptations, in contrast to those species adapted to stagnant conditions. For example, *S. alba* produced wide range of adaptation (hypertrophy of lenticels, adventitious aerenchymatous roots and roots with negative gravitropism) and exhibited increased growth in waterlogged soils in spite of its ecological restrictions to aerated soils. The other riparian species as well as non-riparian (*S. discolor*) produced morphological adaptations as well. It is likely that the wide range of *Salix* adaptations to flooding are a constitutive feature of many species of this genus.

It is worth mentioning that some adaptations such as prolific development of roots or negative gravitropism in the response to water table fluctuations evolved in parallel for different species, inhabiting different continents and systematically distant. *Salix nigra* is a North American species belonging to Section *Humboltdiana* and *S. alba* is a Eurasian species belonging to the Section *Salix*. Both species are typical alluvial inhabitants.

Salix amygdaloides, like *S. nigra*, belongs in the alluvial group inhabiting predominantly riparian zones in North America. It did not produce roots with negative gravitropism. *Salix exigua* occurs most frequently in inundated lower portions of the floodplain, as does to *S. nigra* (Hightshoe, 1998), and did not possess this adaptation.

<u>Similarities in effects of compacted and flooded soil on plant growth</u>

What is the physiological basis for a plant's ability to tolerate compacted soils, and is there any relationship between ability to grow in flooded and compacted soils? Compacted soil is characterized by an increase in density and reduction of porosity, which mechanically restricts root growth and limits water drainage and gas exchange between the soil and the atmosphere. In field conditions compacted soils can be temporarily flooded after rain due to slow drainage and oxygen concentrations may drop at that time. The increase in soil moisture greatly decreases soil resistance and it is possible that wetland species take advantage of such temporarily anoxic conditions to promote root growth and proliferate to a significant depth. The growth of *Salix* in waterlogged soils is consistent with this explanation, which was proposed by Day et al. (1995) for other woody genera.

Many floodplain trees (*Acer negundo*, *A. saccharinum*, *Betula nigra*, *Morus alba*, *Platanus occidentalis*, *Populus* spp., *Taxodium distichum*) are classified as "urban tolerant." This is partially based on their ability to grow and proliferate in compacted urban soils under anaerobic conditions. The relationship of flood tolerance and soil compaction could serve as a basis for tree selection for urban environments, but further research is needed to confirm it. In conclusion, due to their ability to grow in compacted soils many willows can be considered for landscaping in stressful sites. Species of *Salix* are also recommended for planting in soils that are subject to frequent and/or prolonged flooding.

Treatment	Oxygen (%)	CO_2 (%)	Ethylene (µl l^{-1})
Control	21.7±0.16	0.17±0.06	0.13±0.03
Compaction 1	21.0±0.19	0.30±0.06	0.16±0.04
Compaction 2	20.6±0.14	0.62±0.12	0.15±0.03
	$F_{2,68}$=3.34	$F_{2,68}$=12.27	$F_{2,68}$= 0.56
	p=**0.0372**	p=**0.001**	p= 0.576

Table 2.1. Average composition of soil atmosphere, surrounding *Salix* roots during final two weeks of the experiment (n=24) in compaction treatments. Bold type indicates significance at the α = 0.05 level.

Treatment	**Oxygen (%)**	**CO_2 (%)**	**Ethylene ($\mu l\ l^{-1}$)**
Control	21.7±0.16	0.17±0.06	0.13±0.03
Flooding	9.11±0.62	2.15±0.2	1.57±0.09
	$F_{1,45}$=119.8	$F_{1,45}$=97.73	$F_{1,45}$=221.42
	p= **0.0001**	p= **0.0001**	p= **0.0001**

Table 2.2. Average composition of soil atmosphere, surrounding *Salix* roots during final two weeks of the experiment (n=24) in flooding treatments. Bold type indicates significance at the $\alpha = 0.05$ level.

Variable	Below ground		Above ground	
	F_{df}	**p**	**F_{df}**	**p**
species	$F_{11,108}$=28.08	**0.0001**	$F_{11,108}$=23.72	**0.0001**
compaction	$F_{2,108}$=3.53	**0.0327**	$F_{2,108}$=1.06	0.3488
species*compaction	$F_{22,108}$=3.67	**0.0001**	$F_{22,108}$=1.62	**0.05**

Table 2.3. Probabilities of null effects on below and above ground biomass for all species in compaction treatments. Bold type indicates significance at the α = 0.05 level.

Variable	Below ground		Above ground	
	F_{df}	**p**	**F_{df}**	**p**
species	$F_{11,72}$=16.08	**0.0001**	$F_{11,72}$=30.71	**0.0001**
flooding	$F_{1,72}$= 1.81	0.1831	$F_{1,72}$= 0.03	0.8609
species*flooding	$F_{11,72}$=4.87	**0.0001**	$F_{11,72}$=3.56	**0.0005**

Table 2.4. Probabilities of null effects on below and above ground biomass for all species for flooding treatment. Bold type indicates significance at the α = 0.05 level.

Species	Compaction, below ground	Compaction. above ground	Flooding, below ground	Flooding, above ground
S. alba	0.59	**0.05**	**0.05**	**0.08**
S. amygdaloides	**0.014**	**0.01**	**0.009**	0.105
S. cordata	**0.005**	**0.008**	**0.008**	0.231
S. discolor	**0.04**	**0.02**	0.373	0.118
S. elaeagnos	0.302	0.211	0.211	0.119
S. eriocephala	**0.009**	**0.004**	**0.004**	**0.002**
S. exigua	0.505	0.21	**0.002**	0.262
S. hastata	0.48	0.171	0.171	0.151
S. nigra	0.496	0.35	**0.035**	0.249
S. purp.'Nana'	0.951	0.782	0.782	0.782
S. purp.'Stream'	0.737	0.488	0.489	0.868
S. repens	0.759	0.357	0.357	0.907

Table 2.5. Probabilities of null effects on below and above ground biomass for each *Salix* species under various treatments. Significance at the α = 0.05 level is indicated by bold type.

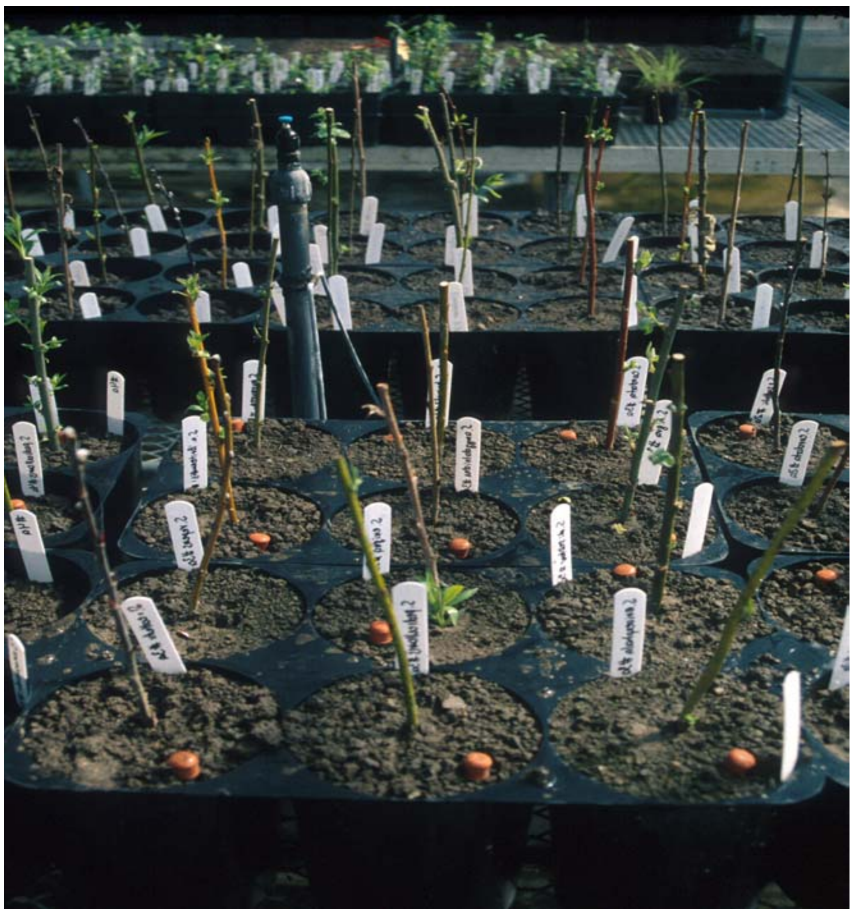


Figure 2.1. Experimental units at time of planting with gas sampling septum.

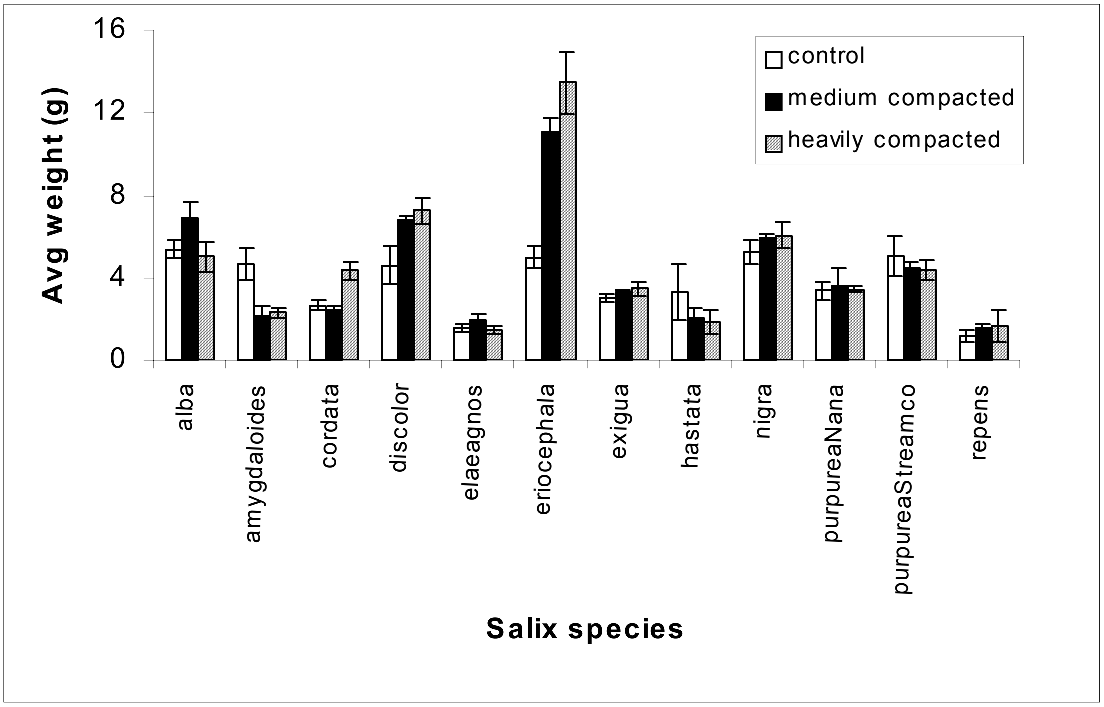


Figure 2.2. Response of root dry biomass of 12 *Salix* species to soil compaction.

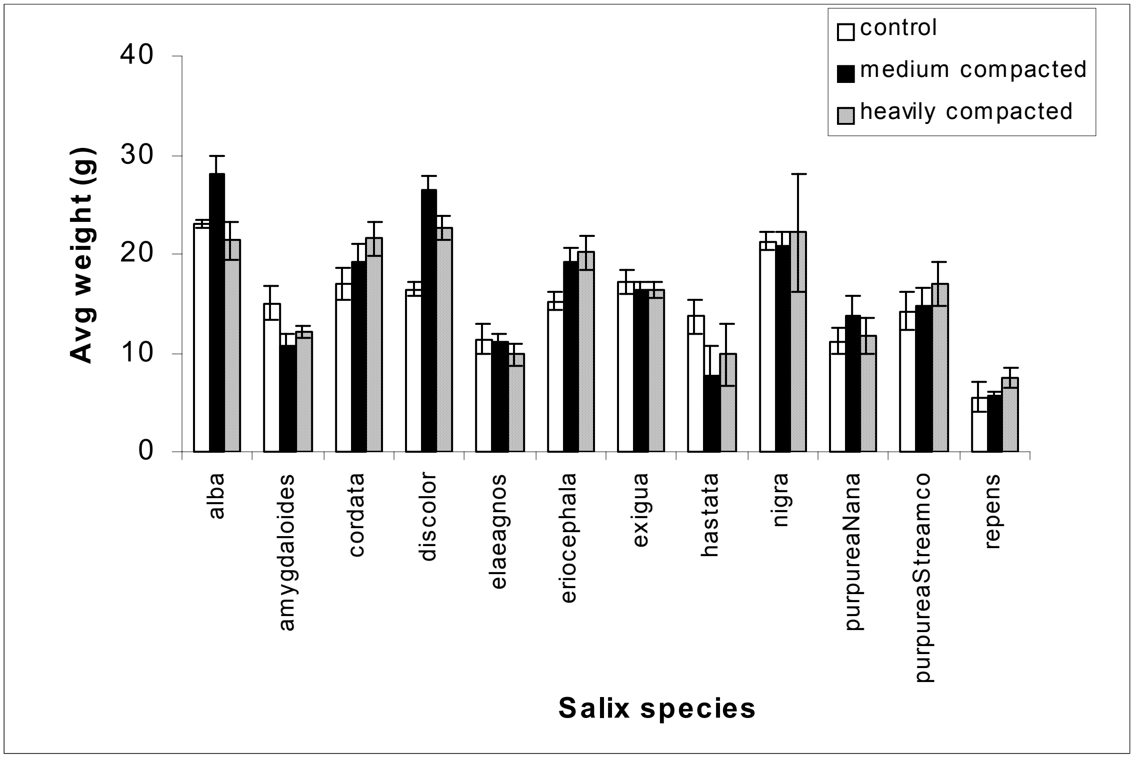


Figure 2.3. Response of shoot dry biomass of 12 *Salix* species to soil compaction.

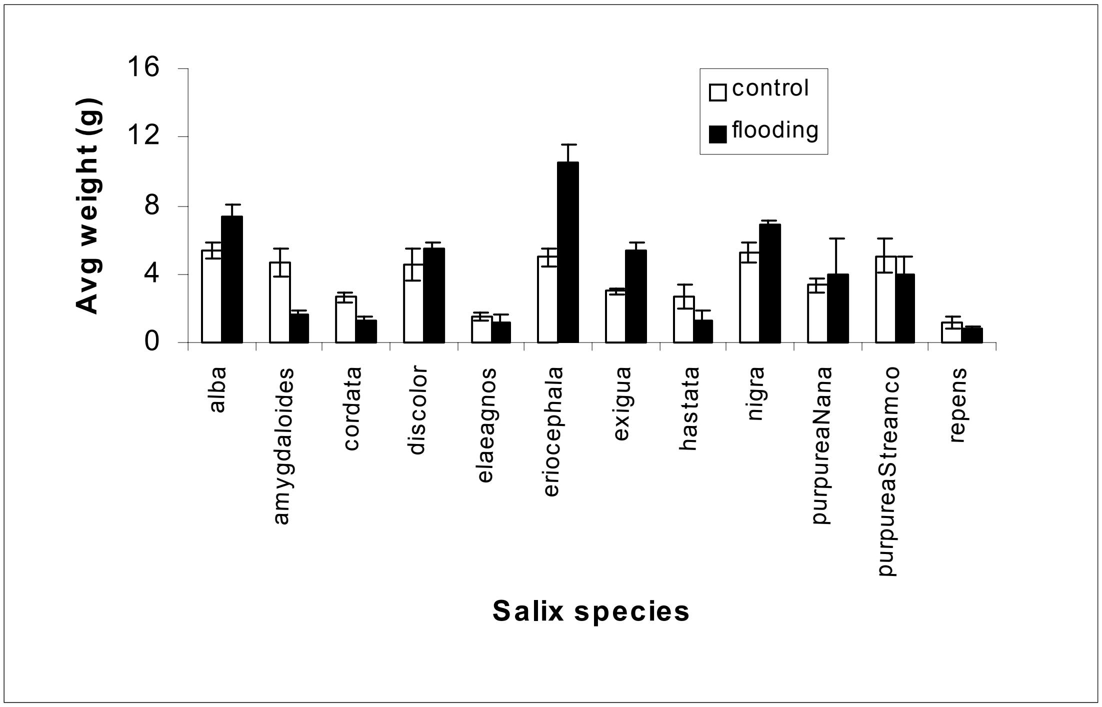


Figure 2.4. Response of root dry biomass of 12 *Salix* species to flooding.

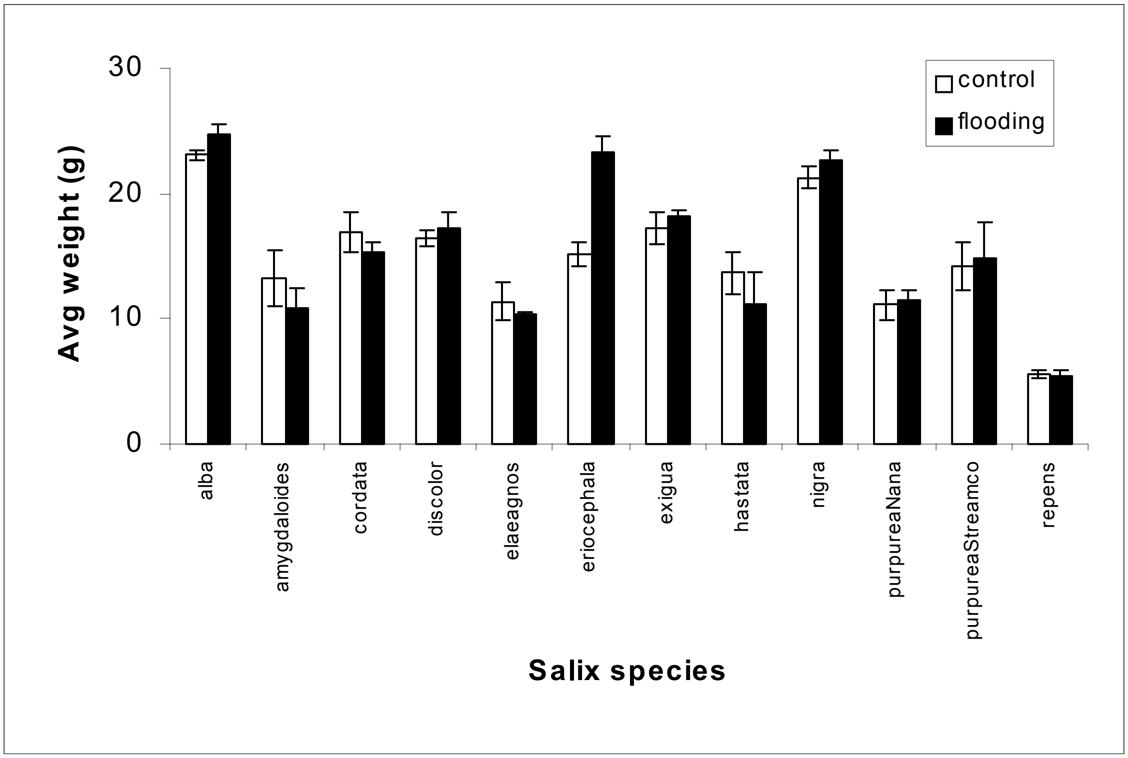


Figure 2.5. Response of shoot dry biomass of 12 *Salix* species to flooding.

Figure 2.6. Hypertrophy of stem lenticels of *S.amygdaloides* in flooded treatments.

Figure 2.7. Dense adventitious roots system of *S.nigra* produced after 21 days of flooding. White thick root contains aerenchymatous cells.

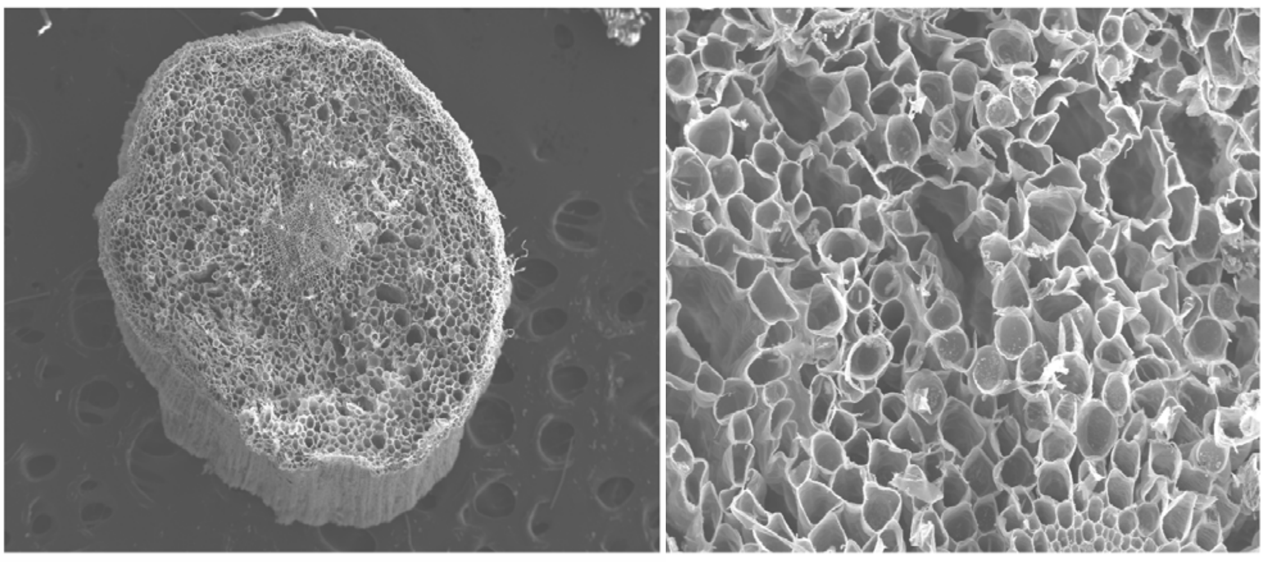


Figure 2.8. Scanning electron micrographs of root cross section 2 cm from the tip with aerenchymatous cells of *S. exigua* under x50 (left) and 250 (right) magnification

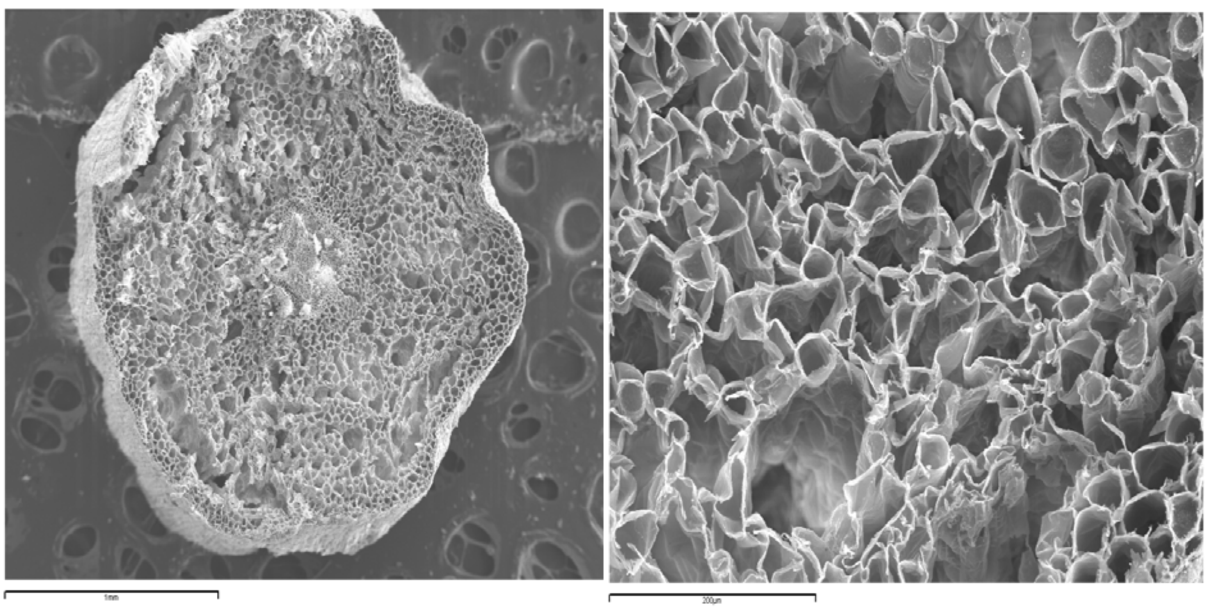


Figure 2.9. Scanning electron micrographs of root cross section 2 cm from the tip with aerenchymatous cells of *S.nigra* under x43 (left) and 230 (right) magnification.

Figure 2.10. Floating root of *S.amygdaloides*, formed after 21 days of flooding.

Figure 2.11. Roots of *S.alba* (left) and *S.nigra* (right) exhibiting negative gravitropism in flooded treatment.

CHAPTER 3

CADMIUM AND COPPER UPTAKE AND TRANSLOCATION IN 5 WILLOW (*SALIX* L.) SPECIES

Introduction

The accumulation of heavy metal in the upper soil layers due to mining, smelting activities, atmospheric deposition and the disposal of sewage sludge onto agricultural land represents a serious environmental problem. Phytoremediation is a new area of research, using green plants to remove, contain, or render harmless environmental contaminants (Cunningham and Berti, 1993). Plants may clean up toxic soil by absorbing pollutants, and those accumulated in plant tissues can be harvested. Phytoremediation is developing in the United States and other countries as a cost-effective solution for cleaning a variety of contaminated sites (Salt et al., 1998). The search for hyperaccumulators--plants capable of sequestering potentially toxic metal in their tissue --has led to intensive screening of many plant species. Metal tolerance in plants varies among genera, species and clones; some herbaceous species, such as grasses and mustards, have been found capable of accumulating significant amounts of metal in their tissues.

The search for fast-growing woody species able to remove metals from contaminated sites has been a focus of recent research in both North America and Europe. Some trees such as *Acer pseudoplatanus* (Turner and Dickinson, 1993), *Salix caprea* (Eltrop et al., 1991), *Betula pubescens* (Kozlov et al., 1995) are known to be able to colonize metalliferous soils.

The idea of using willow for purification of metal-contaminated ecosystems appeared after analysis of ashes from combustion of different biofuels had revealed the high heavy metal content of willow wood (Ostman, 1994). The genus *Salix* comprises about 450 species, which are all easily propagated, fast-growing and tolerant of diverse soil conditions. The ability of *Salix* to resprout after harvesting of aboveground biomass, along with significant transpiration rates and potential production of energy biomass, makes it an attractive group of plants for phytoremediation purposes. Different species of willow, as well as some horticultural clones, vary considerably in their metal translocation patterns and their ultimate tolerance of heavy metals (Dickinson at al., 1994; Riddell-Black et al., 1994). Tolerance of some metals, such as Cd, Cu and Zn has been documented for a few European *Salix* species (Punshon and Dickinson, 1997; Watson et al., 1999). Some temperate Asian species are able to accumulate significant amounts of Fe, Zn and Pb (Ali et al., 1999).

This research extends the study of willows' response to heavy metals to North American species. We hypothesized that New World species of *Salix* would show metal tolerance through continued growth and health in the presence of cadmium and copper. These two metals are of great importance as environmental pollutants because they are very commonly found in industrially contaminated soils and in wastewater and sewage sludge (Salt et al., 1998). Cadmium is not an essential element for plant functioning and can be strongly phytotoxic, causing rapid death (Baker, 1993). Copper is an essential micronutrient for plants, but it can become toxic at high concentrations. It has been proposed that the metabolic mechanism for cadmium and copper detoxification involves two classes of phytochelating peptides in the plant tissue: metallothioneins and phytochelatins (Salt et al., 1998). Metallothioneins are induced by Cu, to which they have an affinity, while phytochelatins bind Cd and Cu. The internal detoxification of metal ions takes place by chelation with organic acid residues and sequestration in the vacuole as well as in leaf trichomes (Salt et. al., 1995). The cell wall of the root can also serve as a storage site and can be very efficient in immobilizing metal ions (Kahle, 1993).

The first objective of this study was to determine the metal tolerance of 5 North American willow species. The second objective was to document the uptake and translocation patterns of the metals: in which tissues were metals stored. Knowledge of the patterns of metal uptake and sequestration is important for environmental projects, where metal translocation into above ground shoots or foliage, as opposed to roots, would be desirable for harvesting.

Materials and methods

The greenhouse experiment was replicated twice: in April-May and August-September of 2000. Ambient temperature fluctuated between 20 and 27^{o}C, average relative humidity was 80% and light followed the changes of the natural environment. Plants for the experiment were set out in randomized complete block design with four replicates. One block consisted of 25 hydroponic units, or treatments, with two factors: 5 species and 5 solutions (control, two concentrations of Cu or Cd).

The willow species used in the study were S. *discolor* Muhl., *S. eriocephala* Michx., *S. exigua* Nutt., *S. nigra* Marsh. and *S. lucida* Muhl. Cuttings of these species were obtained from native habitats in rural Ohio. Hardwood cuttings of uniform 20 cm length had been rooted hydroponically in half-strength Hoagland's nutrient solution for 5 weeks prior to the beginning of the experiment. Each cutting was mounted into a plastic pot cover and set into a pot containing 900 ml solution. The solutions were constantly aerated. After 5 weeks, when the root systems were well developed, the hydroponic solution was replaced with fresh solutions containing either 5 or 25μM additional Cu or Cd (added as $CuSO_4$ or $CdSO_4$). A fifth, control treatment maintained the Hoagland's solution. All solution loss was made up twice a week.

Solution uptake by plants was recorded twice a week by weighing the pots. Measurements of metal concentrations in solution were conducted each 3- 4 days using cupric (Model 9629, ORION, USA) and cadmium (Model 9648, ORION, USA) selective electrodes. At the end of the experiment all plants were harvested and washed; plant material was separated into roots, wood (original cutting) and shoots (leaves and secondary stems), dried in the oven for 48 hours at 70° C, and dry weights recorded. Metal content was determined in dry plant tissues using an Inductively Coupled Plasma Mass Spectrometer (ELAN 6000 ICP-MS, Perkin-Elmer Corporation). Roots, wood and shoots of each plant were analyzed separately. After recording dry weight, all samples (N = 300) were ground, digested with HNO_3 and HF; 0.02 g of the tissue were dissolved in 5 ml of HNO_3 and 1 ml 48% HF in a Teflon beaker. Samples were heated on a hot plate for 5-10 minutes until all organic matter had decomposed; digests were poured into 50 ml plastic bottles, and then made up to volume with deionized water prior to analysis.

A standard protocol to calculate indices of plant resistance to metals involves measurement of the length of the main root in control and metal treatments (Baker, 1993). The cuttings used in this experiment lacked a main root, but developed dense adventitious root systems. Since it was impossible to measure elongation of any single root, the metal tolerance was evaluated based on dry root weight values compared to control.

Statistical Procedure

Data were subjected to analysis of variance (ANOVA) (SAS release 6.11, SAS Institute, Cary, N.C.) and the treatment effects reported were significant according to an F-test at the $\alpha = 0.05$ level. Data for metal concentration in solution was analyzed using the SAS General Linear Model (GLM) procedure and reported as Type III sum of squares. A difference between treatment means of $p < 0.05$ was regarded as significant.

Results

Plant growth

Plant growth in all treatments was estimated through effects on root and shoot dry weight. The addition of metals to the solution caused significant changes of root and shoot weight. All treatment, species, and species x treatment interactions effects were significant (Tables 3.1, 3.2).

Five µM Cd had little inhibitory effects on root and shoot of any species, and *S. eriocephala*, *S. exigua*, and *S. nigra* actually had higher shoot biomass than in the control plants. 25 µM Cd was inhibitory, especially for *S. lucida*, but had not for *S. exigua* and *S. nigra.* Figures 2 and 3 show treatment effects expressed as a percentage of control of dry root and shoot biomass. 5µM Cu increased root and shoot growth of *S. exigua* and *S. nigra*, but 25 µM was strongly inhibitory. Root biomass of *S. discolors* and *S. nigra* decreased less dramatically in 25 µM Cu compared with other species indicating their higher resistance to the metal. Decrease of shoot growth in the 25 µM treatment for most species was not as great as for roots. Roots were most affected by metals; there was a 34-84 % reduction of root weight depending on species in 25 µM of copper compare to 25-58 % reduction in shoot growth.

Overall vitality. Throughout the experiment all cuttings continued active growth and there was 100% survival in all treatments. Wilting and curling of leaf tips were recorded at 25 µM Cu for *S. exigua* and *S. eriocephala*, but the plants continued to grow. No morphological changes were observed for plants in any metal treatment. Prior to metal addition all cuttings had only adventitious roots, and their architecture did not change in the metal solutions.

Transpiration. The addition of both metals to the solution caused significant changes in transpiration rate. There were differences between treatments and species and significant species and treatment interactions (Tables 3.3). Depressed transpiration rates were observed for *S. eriocephala* in most metal treatments with the lowest at 25 µM of Cu where it dropped from 23.0 g/day in control to 16.3 in g/day (Tables 3.4). In *S. nigra* some increase of transpiration was observed in Cd treatments (from 21.4 in control to 22.3 and 24.2 g/day in 5 and 25 µM Cd respectively) but transpiration decreased at 5 and 25 µM Cu to 16.4 and 16.7 g/day. For *S. lucida* the lowest transpiration rate was recorded in 25µM of Cd (16.3 g/day compared to 23.0 g/day in control). For the remaining species it fluctuated less.

Metal concentration in solution. Average Cd concentration in solutions throughout the experiment did not change significantly among all species, but species responded differently to the Cu treatments, where a significant change in metal concentration ($F_{4.42}$=3.06, p=0.03) was recorded for different species (Tables 3.5 and 3.6). Two species (*S. exigua* and *S. eriocephala*) had noticeably lower average concentrations of Cu in solutions throughout the experiment (8.4 and 10.6 µM respectively, while the average for all species was 11.6 µM).

Because of variability in the electrode responses, averages were calculated for concentrations to reveal trends in the data. The average concentration of Cd in the solution decreased with time from 16.1 to 12.0 µM but Cu stayed more constant (14.3µM at the beginning of experiment to 13.7µM at the end) (Table 3.7). The very slight changes of metal concentration in solution throughout the experiment pointed to the inability of plants to avoid metal uptake, and probably metal ion uptake by the roots of trees is directly proportional to concentrations in the solution.

Metal content in plant tissues

We found that metal concentration in plant tissues differed significantly among species, treatments and plant organs (Table 3.8, 3.9). The higher concentration of metal in solution corresponded with the higher concentration of metal in plant and all species accumulated higher amounts of metal in 25 µM than in 5 µM solutions. The highest Cd concentrations were found in *S. exigua* (126.5 µg g^{-1}) and *S. nigra* (192.2 µg g^{-1}). *S. nigra* contained the highest concentration of Cu (116.6 µg g^{-1}).

All species accumulated the highest concentration of Cd and Cu in their roots (Figure 3.3 and 3.4). Cadmium concentration in roots ranged from 75.9 to 577.3 µg g^{-1} in different treatments, with the most found in *S. lucida* at 25µM treatments. The range of Cd content in wood was from 18.3 to 181.0 µg g^{-1} for all species and treatments. The highest amount of Cd in wood was recorded for *S. nigra* (100 and 181.08µg g^{-1} in 5 and 25µM treatments respectively), and *S. exigua* (49 and 90 µg g^{-1}). Foliar concentrations of Cd were the lowest for *S. discolor* (6.45 and 27.44 µg g^{-1}) and for the rest of the species it stayed more or less in the same range

(30-40 and 60-80 μg g^{-1} in 5 and 25μM treatments respectively) with the highest value for *S. eriocephala* and *S. nigra* at 25μM.

The average copper concentrations in the control plants were12.4 μg g^{-1} for roots, 4.5 μg g^{-1} for stems and 5.1μg g^{-1} for shoots. Copper is an essential element for plants, and normal copper concentration in plant material is 2.5-25 μg g^{-1} (Grimshaw et al., 1989); 8 μg g^{-1} is the normal foliar value in *Salix* species growing in unpolluted conditions (Allen, 1989).

The copper concentration in plant organs showed a trend similar to that of cadmium for all species, with maximum concentrations found in roots, and less above-ground organs. Copper accumulation in roots was in the range of 150-1372.7 μg g^{-1}, with the highest concentration in *S. exigua* at 25μM treatments. For most species the Cu concentration in the wood averaged from 8 to 15 and 27 to 36 μg g^{-1} in 5 and 25μM treatments and in the shoots from 13-21 to 14-19 μg g^{-1} in 5 and 25μM treatments. *S. nigra* accumulated the highest Cu concentration in the wood (18.3 and 61.6 μg g^{-1} in 5 and 25μM treatments) and shoots (16.4 and 30.3 μg/g in 5 and 25μM treatments).

The metal content in plant parts was calculated by multiplying dry weight of part by the metal concentration in the respective treatment and the significant differences were found between species, treatments and species and treatments interaction for each part (Table 3.10). The metal content was significantly different between tissues (Table 3.11) ($F_{2.114}$=28.54, $p<0.0001$ for Cd and $F_{2.174}$=30.43, $p<0.0001$ for Cu for all species). Total metal content in whole plant varied between species and treatments (Table3.12) and ranged from 72.7 to 697.6 μg for Cd treatments and from 70.7 to 294.1 μg for Cu treatments (Table 3.13).

The extent of metal translocation to the aboveground organs was estimated based on percentage of distribution between plant parts (Figures 3.7 and 3.8). For most species the highest Cd content was found in wood; it was intermediate in roots and lowest in shoots. An exception was *S. exigua*, which accumulated the highest amount of cadmium in roots in the 5 µM treatments. For Cu treatments the trend was different and the highest amount of metal was found in roots, intermediate in wood and least in shoots. The amount of copper in new growth in 25 µM treatments was lower than that in 5 µM solution.

<u>Relationship between metal uptake from solution and metal concentration in plant</u>

The amount of metal taken up by the plant from the solution calculated through transpiration over 21 days. An increase of Cd content in plant tissue was correlated to metal uptake through transpiration (R^2=0.5) (Figure 3.7) A different pattern of Cu uptake and accumulation shown in Figure 3.8, where Cu content in plants' tissue did not correspond to its calculated uptake from solution. As the experiment proceeded copper was being excluded from plants in 25 µM treatments, so that measured solution concentration declined and then increased (Table 3.7).

Discussion

<u>Plant growth and tissue metal content</u>

The observed ability of *Salix* species to continue growth in the presence of Cd and Cu and to accumulate metals in their tissues determined their tolerance of moderate to high levels of metals. Metal uptake, translocation and growth response varied with metal, application levels, and species. The difference in metal sensitivity between species ranged from stimulation of root and shoot growth to their severe inhibition.

The general trend for copper was the stimulation of growth at 5 μM and considerable depression of growth at 25 μM. Water uptake was also inhibited by 25 μM Cu for all species. *S. exigua* and *S. eriocephala* had noticeably lower average concentration of Cu in solution and higher concentration of metals in roots than other species. The same species exhibited foliar damage at 25 μM of copper but they did not have high leaf Cu, indicating reduced tolerance for this metal.

Willows were less sensitive to Cd than to Cu and plant growth for most species was not inhibited even at high concentrations. Inhibition of growth was evident only for *S. lucida*, for which the highest concentration of Cd was found in roots of the 25μM treatment. This coincided with the lowest transpiration rate, and low values for root and shoot biomass. High Cd concentrations were toxic for this species. In contrast, growth of *S. nigra* and *S. exigua* was stimulated even at high Cd concentration. Cadmium (<50μM) has been shown to stimulate root growth in sugar beets (Greeger and Lindberg, 1986). There is no evidence that cadmium is essential for growth of any organism and further research is necessary to clarify the effect of Cd.

The analysis of total metal content in plant tissues revealed that the metals taken up by the plants goes to the aerial tissues. The copper content of aerial tissues was relatively lower than that of cadmium. Cadmium appears to be more mobile within the plant, so that the highest accumulation was in wood tissues, while new growth also contained appreciable quantities.

Most of the Cu was immobilized in the roots of the willows tested. The metal could be bound to the root surface or absorbed in the apoplast, where its effects are less detrimental. However, elevated levels of metal in aerial tissues indicated that excess Cu must have passed through the endodermis to enter the transpiration stream. But an increase from 5 to 25 μM Cu in solution did not lead to an increase in shoot accumulation. This is evidence of exclusion. Low mobility of Cu in *Salix* has also been observed in previous research (Nissen and Lepp, 1997; Punshon and Dickinson, 1997).

Two basic strategies of plant response to heavy metal were proposed by Baker (1981). Plants are able to detoxify metal ions at different locations. "Excluders" detoxify metals in the roots, whereas "accumulators" transport metal ions to the shoot where they can be stored in the vacuoles of leaf cells. Accumulators are able to dispose of metals through seasonal leaf drop. Our results indicate that *Salix* functions as an accumulator for cadmium and an excluder for copper. But this categorization is not absolute, since some copper translocation to the aboveground tissues was observed. Copper appears to be more toxic for plants and less mobile than cadmium.

Willows vary in their tolerance to Cu and Cd in terms of growth rate, the metal concentration and total metal content. *S. nigra* was tolerant to both metals, indicating that this species possesses <u>general</u> tolerance to heavy metals. *S. exigua* exhibited tolerance to Cd, but not to Cu. The experimental plant material was obtained from uncontaminated soils, so our results suggest an innate tolerance of wild plants to abnormal metal contamination in soil water. Almost all willow species are well adapted to wetland conditions. Talbot and Etherington (1987) suggested that iron toxicity is the cause of waterlogging injury. Plants are able to survive flooding through synthesis of metal-binding popypeptides so perhaps metal tolerance evolved concomitantly with tolerance to flooded conditions.

Prospects for phytoremediation

Phytoremediation requires accumulation of metal primarily in aboveground organs, to facilitate harvesting. A maximum of 0.01-0.02% of Cd of dry matter of aboveground tissues was found in wood of *S. nigra*, in contrast to herbaceous hyperaccumulators that may contain more that 1 per cent of metal in dry matter of leaf tissues (Baker et al., 1988). But the considerable biomass production of willows may increase the efficiency of soil decontamination. The economic viability of metal extraction from *Salix* leaves and stems should be evaluated. Metal recovery from the roots is also possible, but only after final harvest of the plants. In a biofuel production cycle, recovery from root biomass would occur only every 25-30 years (Landberg and Greger, 1994a).

Salix nigra is the most promising North American species for phytoremediation research because of its high total metal content, its ability to translocate Cu and Cd into wood and leaves, and its capacity to maintain high growth rates, especially in Cd treatments. Our results indicate that *S. exigua* was able to maintain high growth rates with high internal concentration of cadmium in the aboveground tissues as well. The ability of S. *exigua* to sucker into dense stands with vast root systems in short periods could also be useful in phytoremediation of Cd contaminated soils.

Future field experiments

Plant behavior in metal contaminated soils could differ from that in solution, so species performance in the field should be evaluated. Other factors affect the growth of field plants:

1) Spatial contamination of soils is heterogeneous, but roots will tend to proliferate in less contaminated regions. This decreases the metal uptake and translocation into the plant. In this research plant roots were in contact with a homogenious hydroponic medium.

2) Mycorrhizae can protect plant roots in heavy-metal-polluted soils and they probably decrease the translocation of metal. It is known that willows benefit from vesicular-arbuscular endomycorrhiza as well as ectomycorrhizal associations (Lodge, 1989). There is evidence that *Betula* tolerance to Zn may depend on an ectomycorrhizal association that limits plant tissue concentration of this metal because of metal adsorbtion to the surface of hyphae (Denny and Wilkins, 1987). In this instance a cell wall, either of the root or of the associated mycorrhizal fungus, can serve as a storage site, thus efficiently immobilizing metal ions belowground (Kahle, 1993).

3) Heavy metal field contamination usually comprises multiple elements. The effect of the interaction between heavy metals on plant growth, whether independent, antagonistic, additive or synergistic, should be studied (Kahle, 1993).

Another perspective for phytoremediation

Our results may be most promising in the area of rehabilitation and reclamation of brown fields sites. This would exploit the potential of *Salix* to continue to grow in metal-contaminated soils that are also severely compacted (Chapter 2). Site stabilization can be achieved with some prevention of contaminant dispersal. The capacity of willows to bind heavy metals to the roots suggest their use as metal filters for water and soil purification, immobilizing pollutants and thus restricting metal movement in the environment. Clones with high root accumulation could be used for construction of buffer zones around landfills and other contaminated sites to consolidate contaminants and prevent their leakage to the environment.

Environmental impact

Due to growing interest of using willow as an alternative biofuel, various agricultural techniques have been proposed. These include fertilization with sewage sludge, which is usually contaminated with metals. The use of initially contaminated soils for biofuel plantation sites has also been proposed. If harvested material is incinerated, the concentration of metals in combustion residue could require special handling of ashes.

From an ecological perspective, metal contamination of vegetation could injure herbivorous organisms that consume willows. There is some evidence that passerine species from subalpine areas of central Norway have high accumulations of Cd in their livers, probably as a result of high consumption of *Salix* seeds (Hogstad, 1996). High concentrations of Cd (9 ppm in twigs during winter) in naturally grown *S. aurita* in Norway resulted in toxic metal intake by moose (Ohlson et al., 2001). From this perspective, only species with low shoot uptake but with metal accumulation in roots should be used for non-urban revegetation purposes.

Variable	**Root weight**		**Shoot weight**	
	F_{df}	**p**	**F_{df}**	**p**
species	$F_{4,45}$ =10.24	<**0.0001**	$F_{4,45}$ =84.37	<**0.0001**
treatment	$F_{2,45}$ =32.08	<**0.0001**	$F_{2,45}$ =28.08	<**0.0001**
species*treatment	$F_{8,45}$ =6.19	**0.001**	$F_{8,45}$ =11.17	<**0.0001**

Table 3.1. Probabilities of null effect on root and shoot growth for all species in Cd treatments. Bold type indicates significance at the α = 0.05 level.

Variable	**Root weight**		**Shoot weight**	
	F_{df}	**p**	**F_{df}**	**p**
species	$F_{4,45}$ =11.87	<**0.0001**	$F_{4,45}$ =85.06	<**0.0001**
treatment	$F_{2,45}$ = 40.02	<**0.0001**	$F_{2,45}$ = 334.23	<**0.0001**
species*treatment	$F_{8,45}$ = 4.10	**0.001**	$F_{8,45}$ = 11.07	<**0.0001**

Table 3.2. Probabilities of null effects on root and shoot growth for all species in Cu treatments. Bold type indicates significance at the α = 0.05 level.

Variable	Cd		Cu	
	F_{df}	**p**	**F_{df}**	**p**
species	$F_{4,45}$ =72.21	<**0.0001**	$F_{4,45}$ =89.91	<**0.0001**
treatment	$F_{2,45}$ =4.02	<**0.0247**	$F_{2,45}$ =35.19	<**0.0001**
species*treatment	$F_{8,45}$ =11.46	<**0.0001**	$F_{8,45}$ =5.07	**0.0002**

Table 3.3. Probabilities of null effects on transpiration rate for all species in Cu and Cd treatments. Bold type indicates significance at the $\alpha = 0.05$ level.

Species	Treatment				
	control	**Cd 5 µM**	**Cd 25 µM**	**Cu 5 µM**	**Cu 25µM**
S. discolor	27.6±0.77	34.9±1.06	31.4±0.88	28.1±0.66	24.4±0.81
S. eriocephala	23.0±0.91	17.6±0.66	17.8±1.08	16.4±1.33	16.3±0.54
S. exigua	28.0±0.71	24.5±1.72	24.1±1.61	27.9±0.55	22.9±0.68
S. lucida	23.0±1.01	22.4±1.07	16.3±0.99	18.6±0.74	18.8±0.89
S. nigra	21.4±0.58	22.3±0.82	24.2±0.55	16.4±0.68	16.7±1.02

Table 3.4. Effect of Cu and Cd on average transpiration rate of 5 *Salix* species (g/day) (n=4) (±SE).

Variable	Cd treatments		Cu treatments	
	F_{df}	**p**	**F_{df}**	**p**
species	$F_{4,42}$ =2.41	0.0646	$F_{4,42}$ =3.06	**0.0266**
treatment	$F_{2,42}$ =1450	<**0.0001**	$F_{2,42}$ =148.0	**0.0001**
species*treatment	$F_{8,42}$ =1.45	0.2050	$F_{8,42}$ =1.03	0.4280
day	$F_{5,42}$ =12.83	**0.0001**	$F_{5,42}$ =10.05	**0.0001**
species*day	$F_{20,42}$ =1.54	0.1190	$F_{20,42}$ =0.82	0.6770
treatment*day	$F_{10,42}$ =3.76	**0.0011**	$F_{10,42}$ =8.30	**0.0001**
species*treatm*day	$F_{40,42}$ =0.93	0.5912	$F_{40,42}$ =0.46	0.9929

Table 3.5. Probabilities of null effects on solution concentration of Cd and Cu for all *Salix* species during the experiment. Bold type indicates significance at the α = 0.05 level.

Species	**Cd treatments (µM)**	**Cu treatments (µM)**
S. discolor	12.13±2.25	12.17±0.95
S. eriocephala	13.07±2.49	10.63±1.01
S. exigua	13.43±2.51	8.43±1.32
S. lucida	12.37±2.32	13.09±0.71
S. nigra	12.59±2.38	13.81±1.14

Table 3.6. Average concentration of Cd and Cu in 5 and 25 µM solution throughout the experiment for each species (n=8) (±SE).

Day	Cd treatments (µM)	Cu treatments (µM)
3	16.12 ±3.7	14.36±3.5
7	16.46±3.71	14.90±3.61
10	10.62±2.72	8.04±1.75
14	10.45±2.86	9.47±2.75
17	11.74±3.17	12.91±0.7
21	12.28±3.21	13.73±4.05

Table 3.7. Average concentration of Cd and Cu in 5 and 25 µM solution for different treatments by day (±SE).

Variable	root		wood		shoot	
	F_{df}	p	F_{df}	p	F_{df}	p
species	$F_{4,45}$ =19.47	<**0.0001**	$F_{4,45}$ =74.03	<**0.0001**	$F_{4,45}$ =30.79	<**0.0001**
treatment	$F_{2,45}$=825.46	<**0.0001**	$F_{2,45}$=379.3	<**0.0001**	$F_{2,45}$=423.1	<**0.0001**
species*treatment	$F_{8,45}$=12.97	<**0.0001**	$F_{8,45}$=21.19	<**0.0001**	$F_{8,45}$=12.5	<**0.0001**

Table 3.8. Probabilities of null effects on tissue metal concentration in Cd treatments for all *Salix* species. Bold type indicates significance at the α = 0.05 level.

Variable	root		wood		shoot	
	F_{df}	p	F_{df}	p	F_{df}	p
species	$F_{4,45}$ =11.47	<**0.0001**	$F_{4,45}$ =39.24	<**0.0001**	$F_{4,45}$ =7.65	<**0.0001**
treatment	$F_{2,45}$=1080.8	<**0.0001**	$F_{2,45}$=487.1	<**0.0001**	$F_{2,45}$=145.61	<**0.0001**
species*treatment	$F_{8,45}$=15.94	**<0.0001**	$F_{8,45}$=20.12	<**0.0001**	$F_{8,45}$=7.36	<**0.0001**

Table 3.9. Probabilities of null effects on tissue metal concentration in Cu treatments for all *Salix* species. Bold type indicates significance at the α = 0.05 level.

Variable	root		wood		shoot	
	F_{df}	p	F_{df}	p	F_{df}	p
Cd						
species	$F_{4,30}$=17.18	<**0.0001**	$F_{4,30}$=10.64	<**0.0001**	$F_{4,30}$=30.04	<**0.0001**
treatment	$F_{1,30}$=25.90	<**0.0001**	$F_{1,30}$=134.9	<**0.0001**	$F_{1,30}$=48.75	<**0.0001**
species*treatment	$F_{4,30}$=2.85	**0.0407**	$F_{4,30}$=0.64	<0.6384	$F_{4,30}$=10.50	<**0.0001**
Cu						
species	$F_{4,45}$=2.01	0.1091	$F_{4,45}$=20.71	<**0.0001**	$F_{4,45}$=34.25	<**0.0001**
treatment	$F_{2,45}$=53.18	<**0.0001**	$F_{2,45}$=197	<**0.0001**	$F_{2,45}$=196.9	<**0.0001**
species*treatment	$F_{8,45}$=1.98	0.0707	$F_{8,45}$=4.40	**0.0006**	$F_{8,45}$=9.55	<**0.0001**

Table 3.10. Probabilities of null effects on root, wood, shoot metal content in Cd and Cu treatments. Bold type indicates significance at the α = 0.05 level.

Species	**Cd treatments**		**Cu treatments**	
	F_{df}	**p**	**F_{df}**	**p**
S. discolor	$F_{2,18}$ =7.8	**0.0036**	$F_{2,30}$=3.91	**0.0311**
S. eriocephala	$F_{2,18}$ =3.41	0.0554	$F_{2,30}$=9.39	**0.0007**
S. exigua	$F_{2,18}$ =19.35	<**0.0001**	$F_{2,30}$=9.86	**0.0005**
S. lucida	$F_{2,18}$ =16.37	<**0.0001**	$F_{2,30}$=5.02	**0.0132**
S. nigra	$F_{2,18}$ =5.48	<**0.0138**	$F_{2,30}$=4.21	**0.0245**
For all species	$F_{2,114}$ =28.54	<**0.0001**	$F_{2,174}$ =30.43	<**0.0001**

Table 3.11. Probabilities of null effects on metal tissue content (root, wood or shoot) for each *Salix* species in Cd and Cu treatments. Significance at the α = 0.05 level is indicated by bold type.

Variable	**Cd**		**Cu**	
	F_{df}	**p**	**F_{df}**	**p**
species	$F_{4,45}$=4.52	**0.0037**	$F_{4,30}$=19.89	<**0.0001**
treatment	$F_{2,45}$=115	<**0.0001**	$F_{1,30}$=99.88	<**0.0001**
species*treatment	$F_{8,45}$=2.21	**0.0446**	$F_{4,30}$=1.41	0.2545

Table 3.12. Probabilities of null effects on total metal content in plant in Cd and Cu treatments. Bold type indicates significance at the α = 0.05 level.

Species	Cd		Cu		
	5 µM	25 µM	0.25 µM	5 µM	25 µM
S. discolor	72.7	309.5	16.3	70.7	248.8
S. eriocephala	218.8	572.8	24.6	249.2	256.9
S. exigua	467.5	697.6	23.8	202	246.7
S. lucida	334.6	558.5	47.9	236.3	294.1
S. nigra	261.5	641.5	15.4	173.4	256.4

Table 3.13. Total metal content in plant (µg) after treatment with metals for 21 days (n=4).

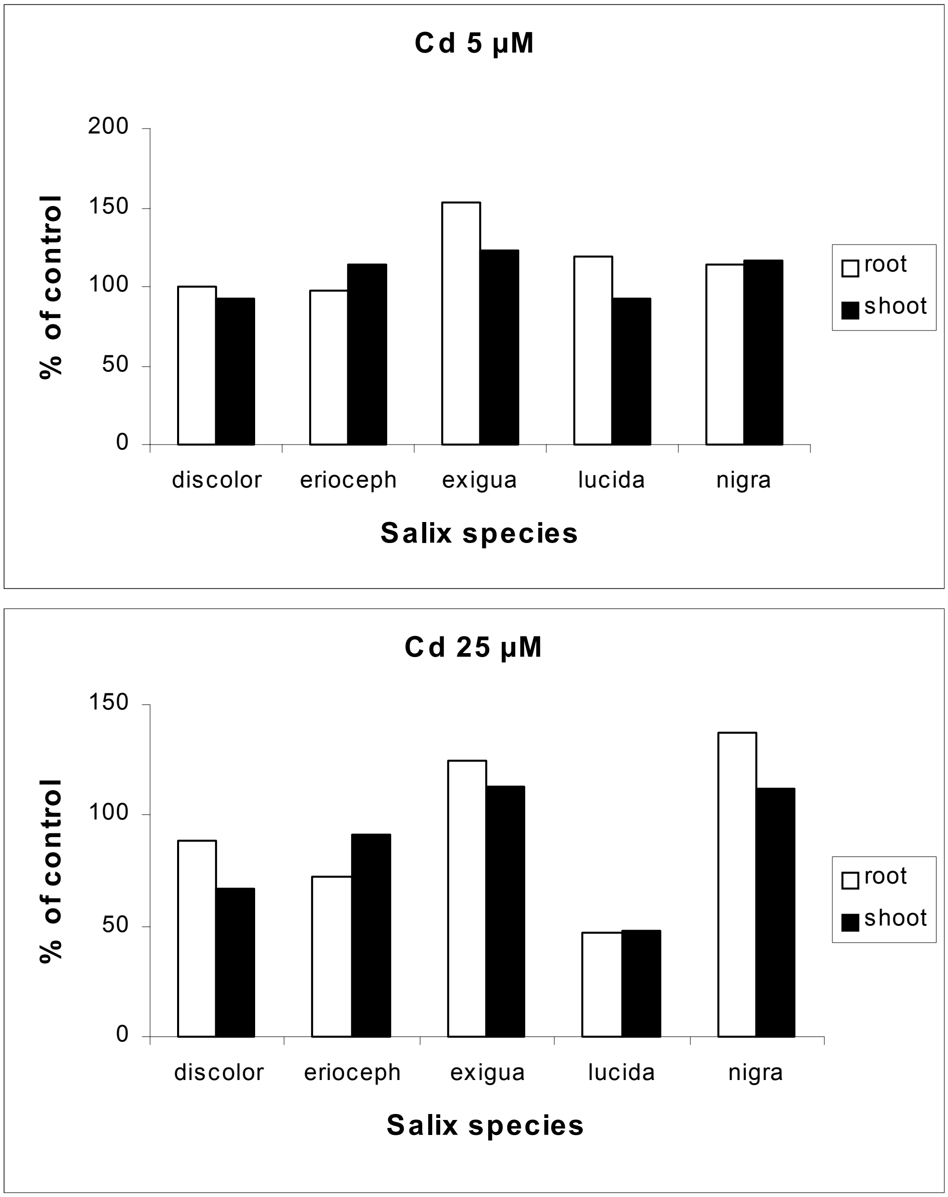


Figure 3.1. Effect of two cadmium concentrations on root and shoot dry weight relative to control for 5 *Salix* species. Plants were treated with Cd for 21 days (n=4).

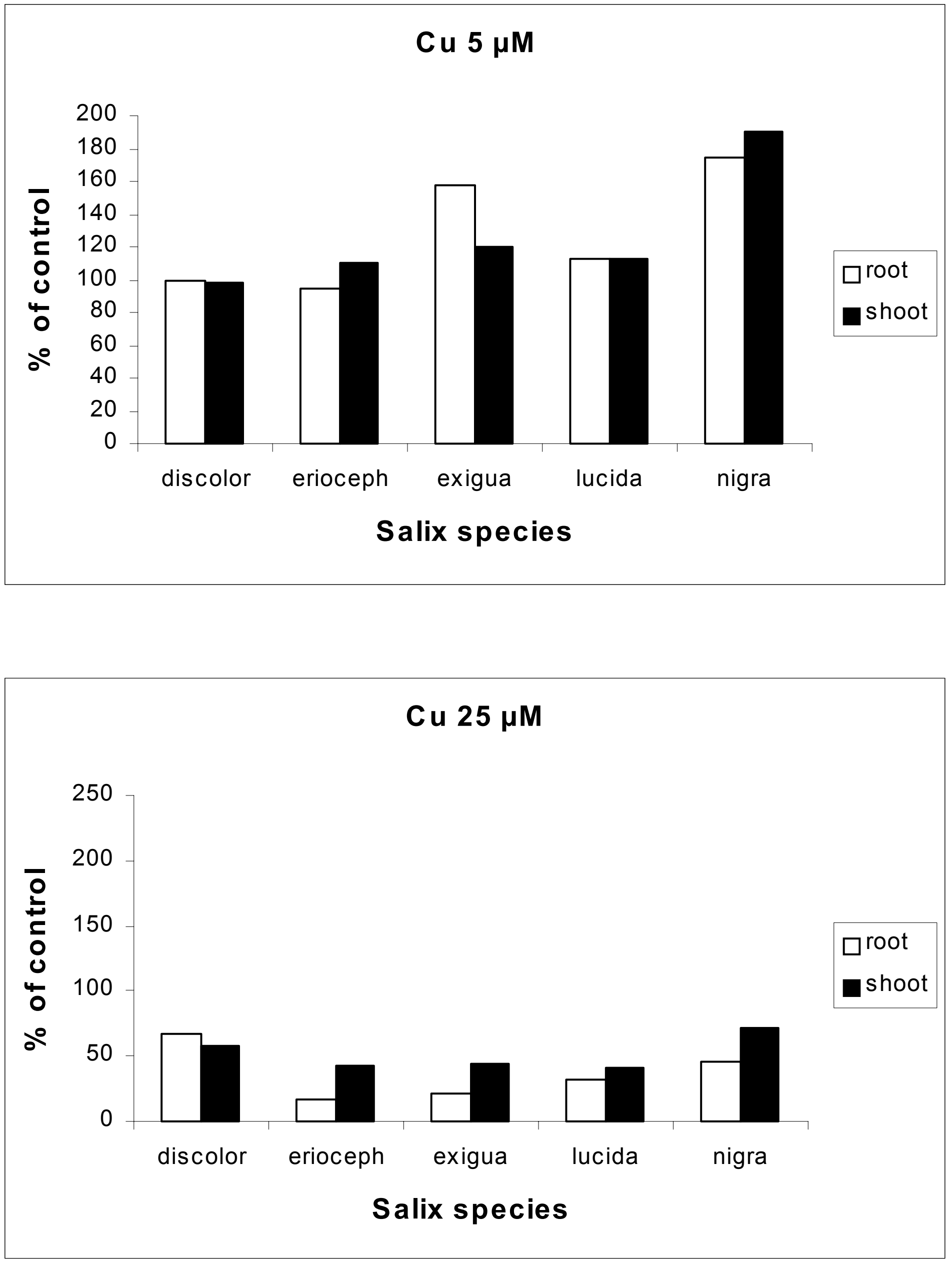
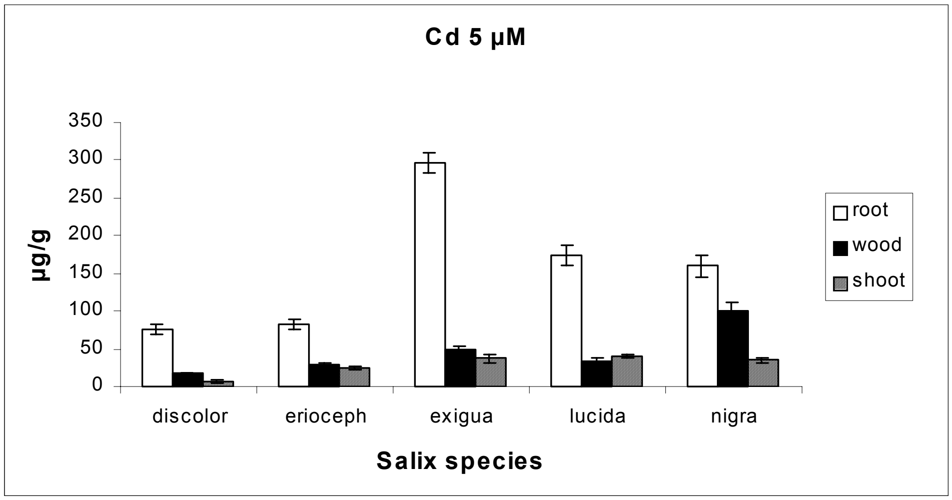


Figure 3.2. Effect of two copper concentrations on root and shoot dry weight relative to control for 5 *Salix* species. Plants were treated with Cu for 21 days (n=4).



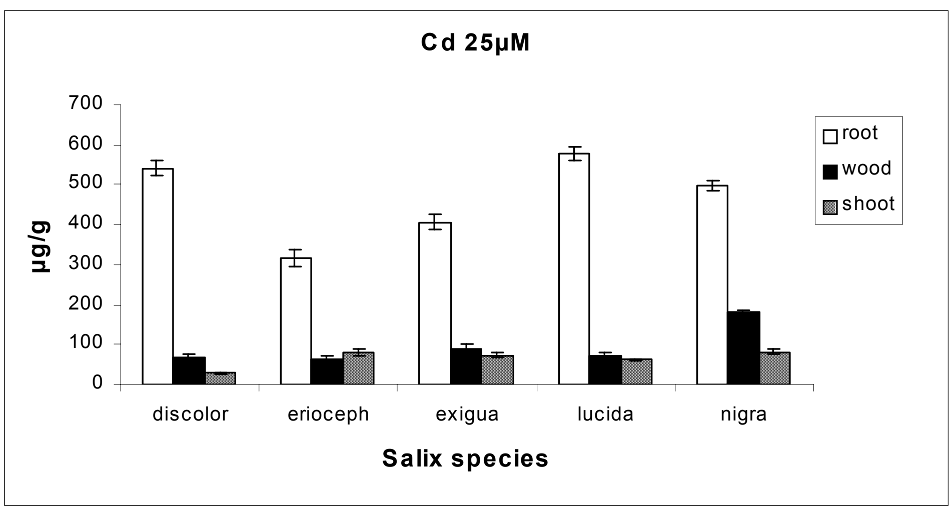
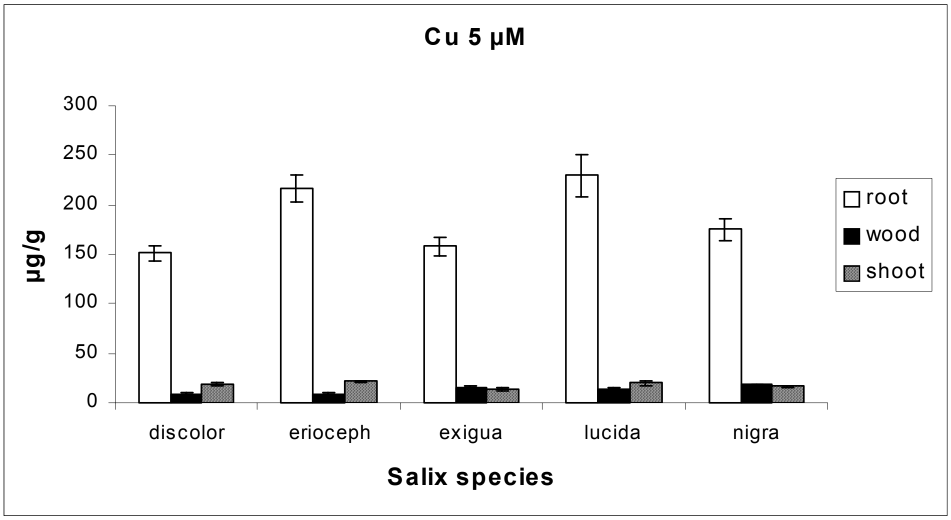


Figure 3.3. Average Cd concentration in dry plant tissues (µg/g) of five *Salix* species after 21 days of growth in metal contained solution (n=4).



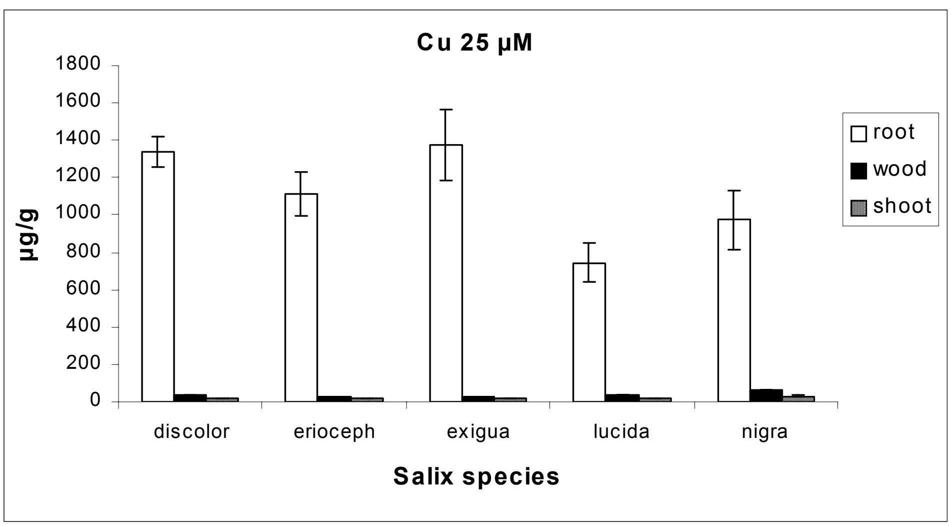


Figure 3.4. Average Cu concentration in dry plant tissues (µg/g) of five *Salix* species after 21 days of growth in metal contained solution (n=4).

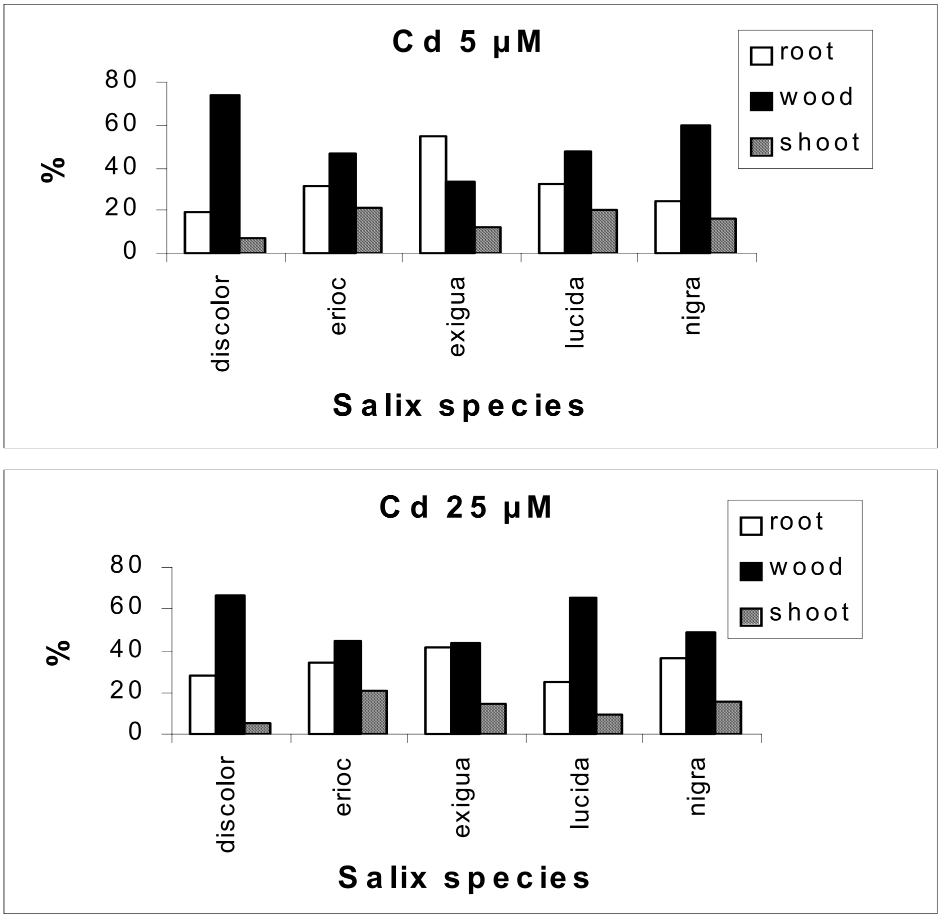


Figure 3.5. Tissue distribution (%) of cadmium in *Salix* species calculated as total Cd content in plant tissue compare with total Cd content in whole plant. Plants (n=4) were treated with Cd for 21 days.

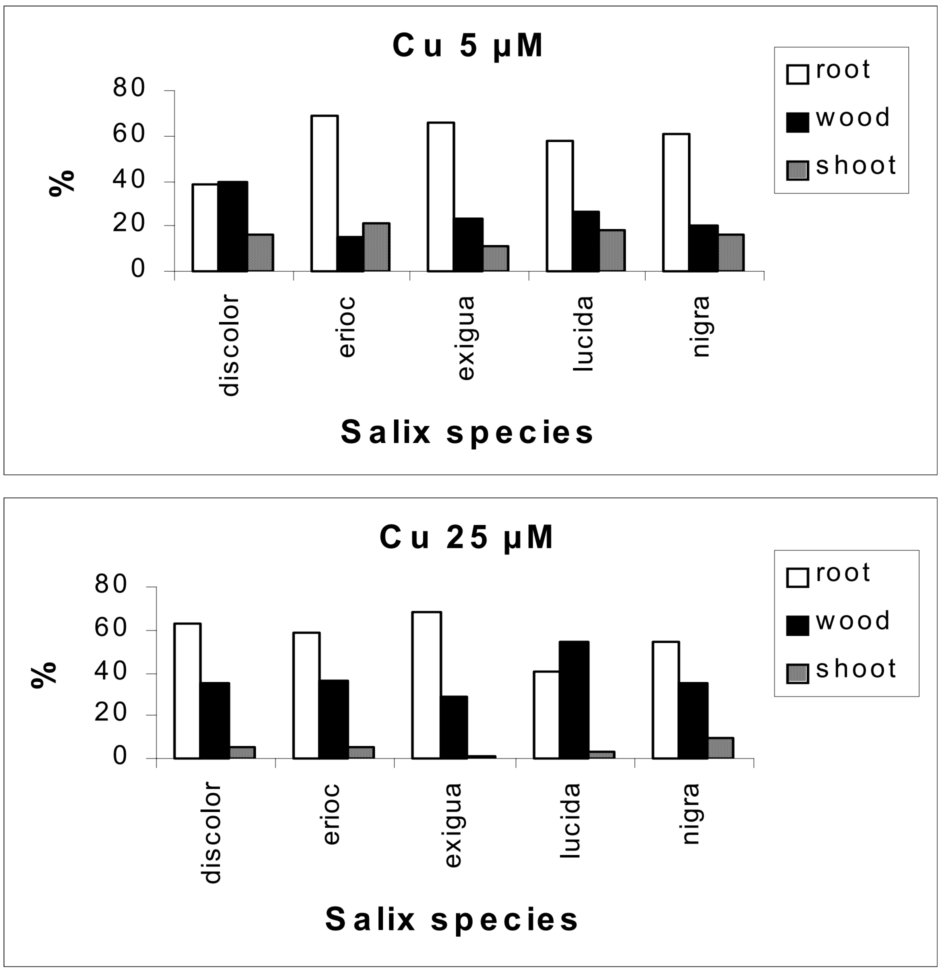


Figure 3.6. Tissue distribution (%) of copper in *Salix* species calculated as total Cu content in plant tissue compare with total Cu content in whole plant. Plants were treated with Cu for 21 days (n=4).

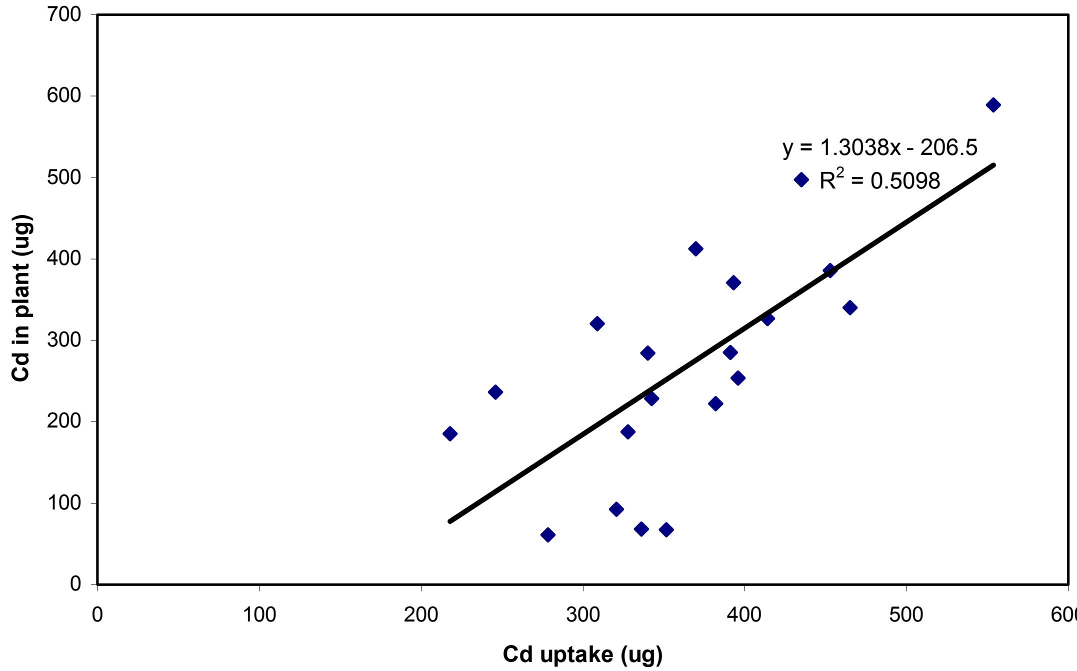


Figure 3.7. Relationship between apparent Cd uptake (water uptake x metal concentration) and metal accumulation in plant tissues for 5 *Salix* species.

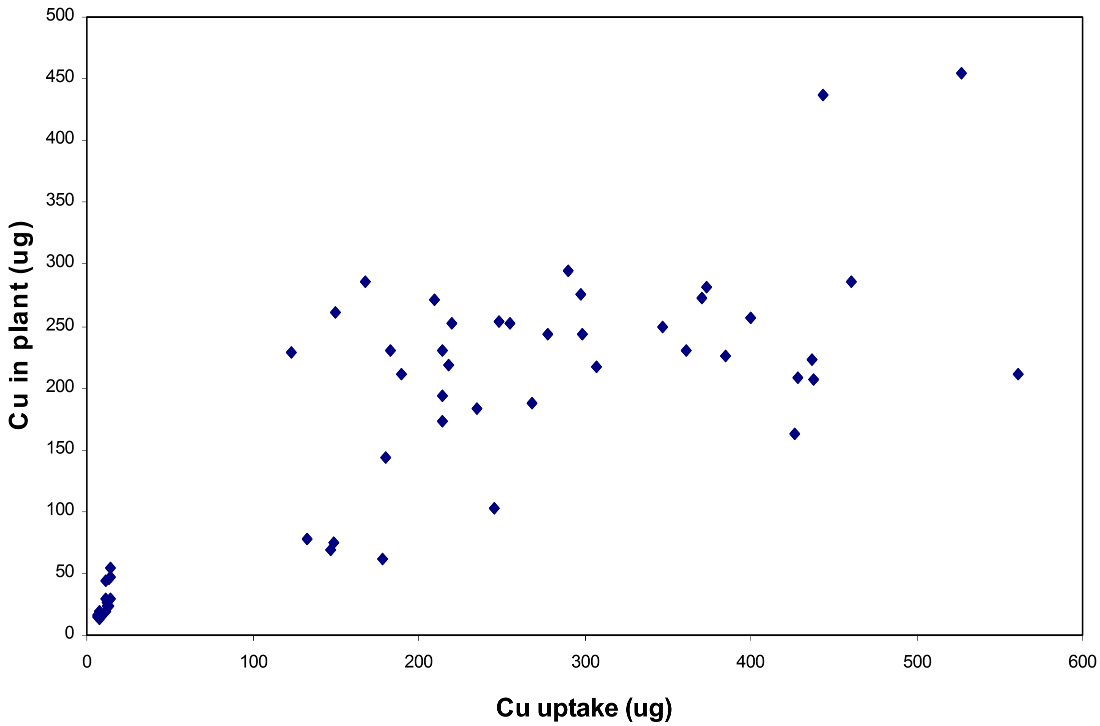


Figure 3.8. Relationship between apparent Cu uptake (water uptake x metal concentration) and metal accumulation in plant tissues for 5 *Salix* species. No trend is revealed.

CHAPTER 4

DIFFERENTIAL RESPONSE OF NINE WILLOW (*SALIX* L.) SPECIES TO ACUTE OZONE EXPOSURE

Introduction

Tropospheric ozone represents an anthropogenic air pollutant with widespread impact on plant health (Skelly et al., 1997). Seasonal ozone doses are potentially phytotoxic over much of the eastern and western USA and northern Europe (Sandermann et al., 1997) causing documented forest decline. Elevated ozone concentrations (50-70 nl l^{-1}) during spring and summer months were observed in urban as well as rural regions of the eastern United States and Canada (Stockwell et al., 1997).

The major source of ozone in the troposphere is its photochemical production from anthropogenic pollutants (nitrogen oxides and hydrocarbons) and the highest levels of ozone observed in summer time during plant active growth. Short-term exposure of plants to elevated concentration may result in acute toxicity with specific symptoms of tissue necrosis caused by membrane disruption and cell death. Longer-term exposure to nearer-ambient ozone concentrations result in chronic toxicity associated with loss of productivity in agricultural and forestry systems.

The ozone enters leaves primarily through stomata, in most cases without injuring the cuticle, and most ozone injury to plant tissue is internal to the leaf. Ozone (O_3) is highly reactive: it breaks down during contact and is not accumulated within plant tissue in contrast to fluoride or oxides of sulfur and nitrogen (Musselman and Hale, 1997). It has been suggested that ozone does not cross the plasmalemma due to its high reactivity, and that the primary site of ozone damage is membrane lipid. Lipid peroxidation is probably the major cause of injury induced by ozone (Heath and Taylor, 1997).

Palisade cells just below the upper surface of the leaf are the first to exhibit injury and most damage is observable primarily on the upper leaf surface (Hill et al., 1970). Visible injury includes chlorosis, necrosis, stippling, bronzing, flecking and/or blackening. Before the development of visible damage, biochemical reactions take place. Ethylene is emitted by stressed cells, which in turn causes greater damage leading to cell death and organ necrosis. The amount of ethylene and its precursor ACC increase in plants upon exposure to ozone (Langebartels et al., 1997). The level of stress ethylene is correlated with visible ozone injury, and it has been suggested (Langebartels et al., 1997) that when ethylene reacts with ozone it produces highly reactive free oxyradicals, which might contribute to plant damage.

Physiological responses of plants to chronic ozone exposure include the loss of productivity associated with the cost for repairing damaged membranes and production of antioxidants, lost photosynthesic capacity due to stomatal closure and degradation of chlorophyll within the cell, and, consequently, decrease of carbon translocation to developing leaves and roots (Heath and Taylor, 1997). As a result the root system may be more severely affected than shoots thus predisposing trees to water stress. The reduction of photosynthesis can affect the ability of trees to harden properly in fall, due to a decrease in soluble sugars and impaired winter hardiness (Wellburn et al., 1997). All these responses to ozone tend to increase plant susceptibility to other stresses and contribute to forest decline.

It has been recognized that plants differ within and between species in their susceptibility to ozone damage. Studies of air pollutant effects on deciduous tree species have included *Prunus* (Fredericksen et al., 1995; Pell et al., 1999), *Quercus* (Samuelson and Edwards, 1993), *Populus* (Berrang et al.,1991; Karnosky et al., 1994; Koch et al; 1998; Lorenzini et al., 1999) and a few other genera. Little is known about relative susceptibility to ozone of different *Salix* species. Horticultural information referring to a few *Salix* species for ornamental use has classified them as sensitive to ozone (Hightshoe, 1998).

Our experiment was to examine 9 *Salix* species to quantify their response to two concentration of acute ozone exposure, as indicated by visual damage assessment. The evaluation of visible injury has been recognized as an illustrative and easily measurable response to ozone for *Populus* species (Karnosky et al., 1992). In addition to comparing the species' response to ozone, we repeated the treatment exposures three times in a summer season, to determine temporal differences for each species' susceptibility at different stages of leaf age.

Materials and methods

Hardwood cuttings of 9 *Salix* species (*S. alba* L.'Britzensis", *S. cordata* Muhl., *S. discolor* Muhl., *S. eriocephala* Michx., *S. exigua* Nutt., *S. humilis* Marshall var. *humilis*,

S. *nigra* Marsh., *S. petiolaris* Sm., and *S. hastata* L.) were obtained from the Ohio State University (Columbus, OH) Chadwick Arboretum collection, or from native habitats in Ohio. Cuttings were rooted in standard soil medium in late April, kept in a mist greenhouse for 5 weeks and then moved into a non-climate controlled polyhouse for 4 weeks prior to the beginning of the experiment.

The experiment was conducted in June-September of 2000 in a whole plant fumigation chambers, modified for ozone treatments, and with completely controlled environmental conditions. Treatments were repeated three times during the season: June 12-13, August 8-9 and September 27-28. On the day preceding ozone exposure, well watered plants were transferred to growth chambers for acclimation. The cuttings were exposed to a single treatment of either 150 or 300 ppb. At moderate levels of ozone (150 ppb) we hypothesized different responses among species. At high levels (300 ppb) we hypothesized that some species would prove to be resistant. Treatments applied for 6h (9AM to 3 PM), on two consecutive days. Growth chamber temperature averaged 22^{o}C, with 77% RH, and a light intensity of 200 µmol m^{-2}s^{-1}. Ozone was generated with an Ozone Gas Generator (O_3 Associates, Kensington, California) and ozone concentration was monitored with O_3 Analyzer (Model 49C, Thermo Environmental Instruments Inc., USA). Ozone was manually turned on and adjusted continually for the whole exposure time to stay as near possible to the specific treatment concentration. Aside from O_3, growing conditions in control chamber were consistent among all treatments. Each species had 4 replications (one plant per pot) for each treatment. Foliar injury was recorded 48 h after the end of the treatment. Data collection noted the presence or absence of leaf damage, and the proportion of injured leaves to uninjured leaves per plant. In some cases, a light was shone through the leaves for better assessment.

Data were subjected to SAS General Linear Model (GLM) procedure and reported as Type III sum of squares (SAS release 6.11, SAS Institute, Cary, N.C.) to determine the differences in percent of visible damage. Species and treatments were used as factors and data was analyzed two ways: using months as replications and using month as repeated measurements. A statistical difference between treatment means of $p<0.05$ was regarded as significant.

Results and discussion

Description of damage

In most treatments the symptoms consisted of chlorotic mottling (small brown necrotic spots), or stippling on the adaxial surface of the leaf. Chlorotic mottling with diffuse borders occurring in irregular pattern, caused by plasmolysis of cell content and cell death, are typical for ozone damage and distinct from damage caused by other air pollutants (Miller et al., 1997). In a few cases tip necrosis and tip-burn was caused by high ozone concentration. Leaf veins were usually not affected and most tissue injury was inter-veinal. Damage was not observed in any unfolding foliage, for any of the species, and most injury occurred on mature leaves.

After the termination of exposure some leaves showed little injury, but developed visible symptoms hours later. It has been previously reported that symptoms of ozone damage may take place hours or days after exposure (Langebartels et al., 1997), which is probably related to the timing of ethylene biosynthesis. Premature leaf senescence of damaged foliage took place, resulting in early leaf abscission of those leaves. Overall plant response to ozone depended upon the ozone concentration (treatment), time of exposure (month), and on species, as well as upon the interaction of those variables (Table 4.1 and 4.2).

Concentration

The ozone concentrations (150 and 300 ppb) revealed differences in response. Throughout the repeated measures analysis the plant damage was greater with higher ozone concentration ($F_{1,54} = 155.47$, $p < 0.001$). Young plants were more resistant to ozone and in the June treatment some species (*S. discolor*, *S. exigua*, *S. humilis*, *S. alba*, *S. nigra*) were not greatly affected by either concentration, ($F_{1,54} = 0.66$, $p = 0.4196$) (Table 4.2). As the season progressed, however, the treatment effect became significant; damage in August was affected by concentration level ($F_{1,54} = 34.89$, $p < 0.0001$) and more so in September ($F_{1,54} = 137.05$, $p < 0.0001$).

Time (month) of exposure

Changes in sensitivity of species to ozone depending on month of exposure were observed ($F_{2,194}=77.65$, $p< 0.0001$) (Table 4.1). The youngest plants in June were more resistant to ozone and leaf injury became more severe as the season progressed (Figure 4.1 and 4.2). In September percentage of damaged leaves was the highest.

It has been reported that plant response to pollutants depends upon the developmental and metabolic state of the plant (Hill et al., 1970). As the plant ages injury becomes more visible. Susceptibility to ozone was the greatest after maximum leaf expansion occurred, which possibly relates to maximum amount of intercellular space in palisade layer. The concealment of visible symptoms by the high content of leaf pigment in summer time and the reduction of natural pigmentation in autumn (Langebartels et al., 1997), could contribute to this effect as well.

Species effect

Wide range in ozone tolerance was found among species of *Salix*. A significant species effect was recorded during each treatment in June, August and September (Table 4.2). Nine *Salix* species could be classified into three groups on the basis of sensitivity: the most sensitive with average leaf damage throughout the season more than 40% of injured leaves (*S. hastata* and *S. eriocephala*); moderately sensitive, with percentage of injured leaves in the range of 20-40 % (*S. alba* 'Britzensis", *S. cordata*, *S. exigua*, *S. petiolaris*) and the least sensitive with average leaf damage less than 20% (*S. discolor*, *S. nigra* and *S. humilis*). The two extremes on the range of sensitivity were *S. humilis*, which developed only slight injury (4.4% leaves averaged throughout season) during all season, and *S. hastata* whicn appeared to be very sensitive (79.2% leaves) (Table 4.3). The rest of the species had intermediate sensitivites.

We were unable to determine the lowest concentrations of ozone to cause injury in *S. hastate*. Even in the June exposure to 150 ppb of ozone the average amount of damaged leaves was 67.9% (Figure 4.1). Future research of symptoms at lower ozone concentration of sensitive species such as *S. hastata* could clarify its potential as a bioindicator of air pollution to alert human (Tingey, 1989). The identification of low threshold for injury for this species can help recognition of a pollutant in the atmosphere and its level based on dose-response relationship.

Ecological inferences

Because stomata plays a prominent role in ozone uptake and the difference in stomatal conductance could affect the sensitivity of different species (Langebartels et al., 1997; Skelly et al., 1997). The foliar sensitivity of many *Salix* species probably result from high stomatal conductance, since willows are typical mesophytic or wetland species. *Salix humilis* var. *humilis* was found to be the most resistant to foliar injury. In native habitats, *S. humilis* var. *humilis* (Upland willow) often occur in dry open areas (Argus, 1986), and cuttings for the experiment were collected in an area of sand dunes. Greater ozone resistance of *S. humilis* may be partially explained by its ability to grow in xerophytic conditions, where it evolved a strategy for avoiding drought stress through stomatal closure. It is possible that ecological differentiation of species responsible for differences in pollutant uptake and the sensitivity to ozone could be linked to sensitivity to other stresses, such as drought. More detailed information about the ecological range of individual *Salix* species would be required to confirm this supposition.

Marked interspecific differences in ozone tolerance among *Salix* species and our documentation of both ozone-sensitive and ozone-tolerant species may enable future work to use the genus as a model for comparative studies of ozone sensitivity at the organismal, cellular, and molecular level as well as to investigate the effects of chronic ozone exposure on plants. Cumulative effects on the same plant in the same season is a common urban problem of chronic ozone exposure, which we did not study here. The selection of species for future study of chronic ozone exposure and possibly field study could be guided by these experiments.

Variable	F (df)	P
Treatment	$F_{1,194}$ =72.49	<**0.0001**
Month	$F_{2,194}$ =77.65	<**0.0001**
Treatment*month	$F_{2,194}$ =22.86	<**0.0001**
Species	$F_{8,194}$ =47.65	<**0.0001**
Species*treatment	$F_{8,194}$ =3.56	**0.0007**

Table 4.1. Probabilities of null effects on ozone leaf damage for 9 *Salix* species that were exposed for 6 hours to 150 or 300 ppb of ozone using months as replications. Bold type indicates significance at the α = 0.05 level.

Variable	June		August		September	
	F (df)	p	F (df)	p	F (df)	p
Treatment	$F_{1,54}$ =0.66	0.4196	$F_{1,54}$ =34.89	<**0.0001**	$F_{1,54}$ =137.0	<**0.0001**
Species	$F_{8,54}$ = 49.84	<**0.0001**	$F_{8,54}$ = 36.56	<**0.0001**	$F_{8,54}$ = 31.55	<**0.0001**
Species*treatment	$F_{8,54}$ =0.91	0.5146	$F_{8,54}$ =1.83	0.0922	$F_{8,54}$ =10.07	<**0.0001**

Variable	Average across months	
	F (df)	p
Treatment	$F_{1,54}$ =155.47	<**0.0001**
Species	$F_{8,54}$ =102.19	<**0.0001**
Species*treatment	$F_{8,54}$ =7.63	<**0.0001**

Table 4.2. Probabilities of null effects on ozone leaf damage for 9 *Salix* species that were exposed for 6 hours to 150 or 300 ppb of ozone using months as repeated measurements. Bold type indicates significance at the α = 0.05 level.

Species	Leaf damage (%)
S. hastata	79.2
S. eriocephala	43.2
S. alba 'Britzensis'	37.1
S. cordata	34.8
S. exigua	30.2
S. petiolaris	25.0
S. discolor	16.8
S. nigra	9.9
S. humilis	4.4

Table 4.3. Average leaf damage for 9 *Salix* species, expressed as a percentage of injured leaves, averaged over the experiment when treated with 2 concentrations of ozone in June, August and September (n=24).

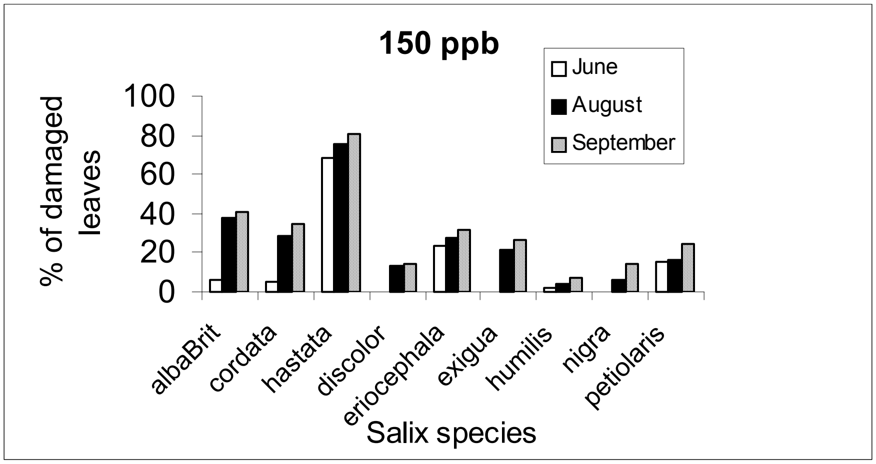


Figure 4.1. Average leaf damage of 9 *Salix* species expressed as a percentage of injured leaves, when treated with 150 ppb concentrations of ozone for 6 h. in June, August and September (n=4).

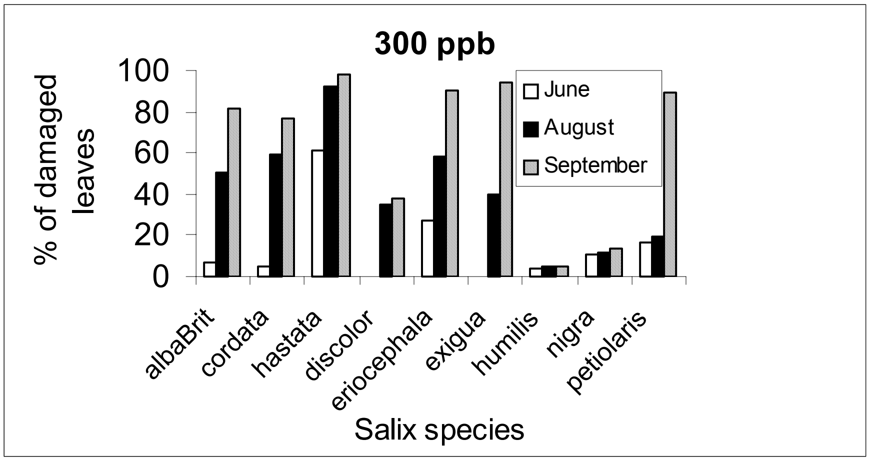


Figure 4.2. Average leaf damage of 9 *Salix* species expressed as a percentage of injured leaves, when treated with 300 ppb of ozone for 6 h. in June, August and September (n=4).

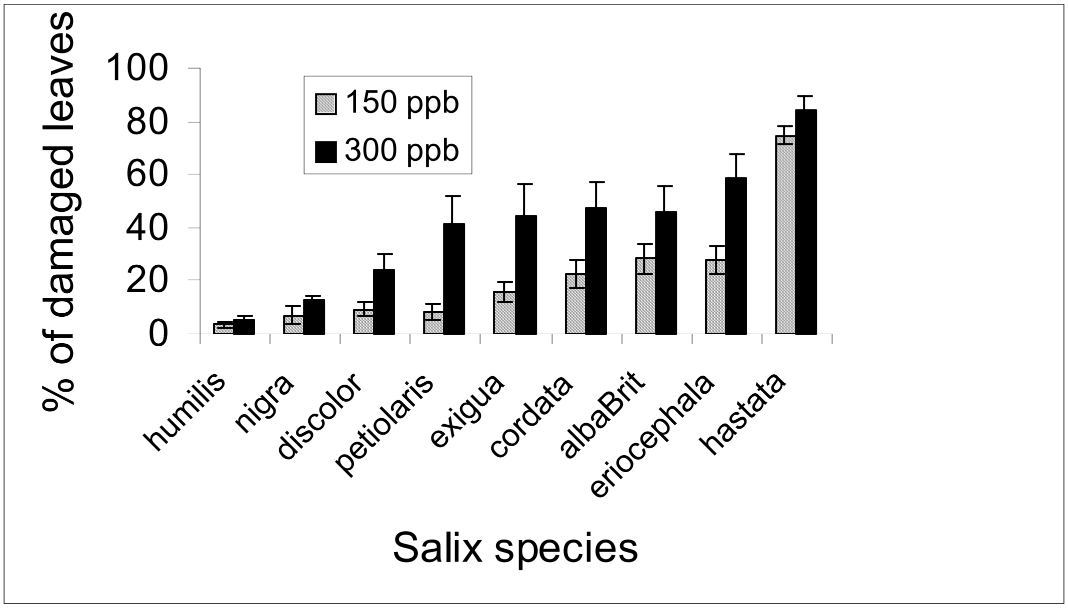


Figure 4.3. Mean leaf damage of 9 *Salix* species, expressed as a percentage of injured leaves, averaged over the experiment when treated with 2 concentrations of ozone in June, August and September (n=12).

CHAPTER 5
EVALUATION OF WILLOW (SALIX L.) SPECIES FOR FLORAL CUT STEM PRODUCTION

Introduction and Methods

Production of woody branches for the specialty cut flower market can be profitable, with low initial investment. Ornamental branches for winter and early spring harvest can be a unique production niche for small farmers and non-agricultural land-owners, offering an opportunity to supplement income during the otherwise dormant season. Woody cuts from trees and shrubs may have not only floral display (e.g., forsythia and quince), but can be valuable to the floral industry for structure, texture, longevity, and relatively lower cost than other floral crops. In general, willow species are relatively care-free, requiring minimal cultivation, supplemental irrigation, fertilization, or other inputs. Common pussy-willows are very popular, and have long been a staple component of spring bouquets, but there are many worthwhile species and cultivars that have not been commonly used in the trade.

From over 150 willow taxa (Appendix), we selected 20 species and cultivars, both North American and Eurasian that were known or appeared to have promise for the floral industry. The willows were grown in open field conditions for four years in central Ohio, USDA zone 4/5, at The Ohio State University Chadwick Arboretum and the Waterman Agricultural Laboratory in Columbus. Detailed evaluations of all aspects of growth, form, hardiness, disease susceptibility, as well as floral and ornamental characteristics, were made annually.

The value of cut willow stems for florists is characterized by:

1) Availability of ornamental stems with catkins during late winter, when other flowers are scarce and expensive, and usually shipped from distant sources.
2) Long (more than 0.5 m [18 in]) stems length is valued for flower arrangements, and catkins provide attractive inflorescences. The strong flexible branches ship and store well, and have a variety of design uses.
3) Prolonged harvesting and storage capability, in addition to the possibility of drying for the preserved-flower market.
4) Reliability and durability of the shrubs, due to low susceptibility to winter damage or spring frost, and the reduced risk of premature blooming (as occasionally happens with some woody species in fall or winter under warm weather conditions).
5) Production potential over the wide range of temperate regions of the USA and Canada. Because of insufficient winter chilling, most willow species cannot be grown in South America for the floral market.
6) Maintenance based on organic principles due to low pest and disease intensity if the basic nutrition and water requirements are fulfilled.

7) Marginal land or areas contaminated with certain pollutants and not suitable for other crops can be efficiently used for willow production.
8) Sustainability of production: harvesting from the same plants for many years reduces labor intensity. The production of a large number of stems from a single plant is advantageous and decreases cost of production.

Structure and development of willow stems and flowers

Willows are dioecious woody plants, having male or female inflorescences (commonly known as catkins) borne on separate plants. Male catkins are typically showier than the females. Most willows flower in very early spring either before foliage emerges, or simultaneously with the first leaves. Unlike prostrate and more determinate alpine and arctic willows, most of the species described here exhibit "free growth" typical of lowland *Salix* species, resulting in continuous growth of stems throughout the season, often to considerable length (up to 2 m [6.5 ft]). Shoot tips commonly abort in all willows, and the new growth begins in the development of an axillary bud from the preceding year (sympodial growth). After the abortion of the tip, a clean-cut abscission scar is pushed to one side and becomes unnoticeable.

Two kinds of buds are found on willow stems: generative or flower buds that occur mostly on the upper portion of the branch, and vegetative or leaf buds that occur below the inflorescences. Flower buds form during the preceding year, containing the inflorescence (embryonic flowers along with several rudimentary leaves) enclosed in a single bud scale. The development of flower buds continues throughout the winter; when the inflorescence expands in late winter or early spring, it pushes off the bud scale. After the bursting or loss of the bud scale the inflorescence resembles a single structure of wooly hairs – the catkin (“pussy “ in English usage) with silky hairs covering each bract, which is subtends to a single flower. At this stage the inflorescence is very dense, and the individual flowers are tightly grouped.

As development progresses the catkin, consisting of a dense spike of apetalous (no petals) unisexual flowers, increases until reaches its maximum size: this is the optimal time for harvesting. Shortly after this stage, a very noticeable differentiation of anthers or pistils takes place. The catkin will elongate, losing its density, and at this point it is too late to harvest the stems. Actual anthesis starts when the male flower displays filaments with bright anthers that shed copious pollen, while females will exhibit less showy, gray-green, capsules (ovaries) with open stigmas. Dramatic pollen colors can be displayed by male flowers at anthesis, with anthers ranging from deep red to yellow and orange, but this phase is ephemeral and lasts only for a few days. When the flowers senesce, the last stage is the abscission of the catkin. The entire inflorescence is shed, leaving conspicuous scars where accessory buds will later develop. Female catkins remain longer on the stem, elongating as the fruit matures and abscising only after seed dispersal, some 8-10 weeks after fertilization.

The species described below differ markedly in size, density and shape (oblong, ovoid, round, cylindrical) of inflorescences. Color of catkins is determined by the color of the bracts and particularly by the color of the bract hair. Direction of the hairs on the inflorescence is important for light reflection, as on the nap of velvet fabric. In some species the bract hairs are multidirectional (*S. amplexicaulis*, *S. hookeriana*) and the inflorescence is not shiny. A few species have ornamental value for characteristics other than the catkin dislay. Some have attractive winter stems with stout, brightly colored buds (*S. caprea*, *S.* x*tsugaluensis* 'Ginme", *S.* x*wimmeriana*), while the others are valued for their stem shape, such as *S. babylonica* 'Tortuosa', the corkscrew willow.

There is a considerable difference in phenology among described species (Figure 5.1). The length of the actual harvesting period, or the time between when the catkin reaches its maximum size and when stamens become visible, also differs depending on species: *S. acutifolia* can be harvested for only one or two weeks, while some other species (*S. koriyanagi*, *S. gracilistyla*) have a wider window for harvesting, lasting as long as four weeks. The precise timing of phenological phases can fluctuate from year to year depending on weather conditions, but the sequence of blooming and leaf emergence remains consistent. Those species valued for attractive branches (bark color or stem shapes) can be harvested any time from November to March. To lengthen the market season we recommend the use of several different species and cultivars to provide a long production period.

It is important to use selected clones for flower production, since great variation in the structure of generative buds can occur. Willows are optimally grown in ordinary loamy soils, but many are tolerant of compacted and flooded conditions (Chapter 2). All willows can be very easily and quickly propagated in early spring by stem cuttings, which will root in days. It will usually take 2-3 years to produce plants large enough for the harvesting of saleable stems. Aside from general woody plant maintenance, cut-stem production also requires the removal of terminal growth to promote thicker, shrubby appearance. Annual severe pruning or coppicing produces straighter and longer single-stemmed branches. Left unpruned for years, branches develop side spurs and are generally less suitable for cut flower production. Annual harvesting of stems will stimulate further growth. When all cultural requirements are satisfied, willows are much less prone to disease or insect damage, so that pest management in the field is usually not necessary.

Our specific descriptions emphasize those species with the most ornamental stems and qualities important to the floral industry. All measurements refer to well-developed shoots at the end of the growing season. The length of stem in the descriptions refers to the length of annual cut stems that can be achieved by coppicing, or cutting to the ground. The diameter of stems is measured at two points: the upper, which is below the fourth bud, and lower, at the base of the stem. For catkin production the precocious species (those that flower before the opening the leaf buds) should be grown, and male specimens are preferred.

Further research of annual yield, cost of production, consumer value and environmental benefits, will assist growers in devising successful strategies for ornamental cut-willow production for specific site conditions.

Species descriptions

Salix acutifolia Willd.

Size: 4-6 m high and 2-4 m wide.

Stems: 1.20-1.6 m long; slightly curved, flexible; small (20-30 mm) die back; glabrous, red-purple, covered with white bloom. Diameter 2 mm at the tip and 5 mm at the base. Yellow inner bark.

Buds: Flower: 12-15 x 6-8 mm, conical, with attenuate tip, purple brown, pubescent at the base; leaf: 5 x 3mm, the same color as stem. Position of flower and leaf buds: the top 4-5 buds are leaf, then 50-60 cm flower.

Inflorescence: 20 x 10-12 mm, ovoid, light gray, almost white, shiny; inflorescence directed at acute (15-25^{o}) angle to stem axis; flower bracts densely pubescent outside, black and red inside, 3 tiny rudimentary leaves surround the inflorescence; anthers yellow.

Native habitat: Eastern Europe; popular in cultivation.

Hardiness: Zone 4-6.

Phenology: Losing most bud scales in January, during the middle of February the catkins reach maximum size; at the end of February first stamens are visible; anthesis 10 days later.

Notes for catkins production: Catkins are prolific and dense (7 per 10 cm). One of best species for catkins production, and unique for its purple stems with white blooms. Bloom is especially pronounced at the base of two year old stems. This species survives on dry, sandy soil.

Salix aegyptiaca L. (syn. *S. medemii* Boiss., *S. muscina* Hort.)

Common name: Armenian willow, Musk willow

Size: 4-8 m high and 2-4 m wide.

Stems: 0.60-0.8 m long; straight, rigid, thick even at the tip; gray-green at the upper portion, green at the base, tip pubescent, base glabrous. Diameter 4-5 mm at the tip and 10 mm at the base.

Buds: Flower: 8-9 x 6-7 mm broadly conical with 2 ribs, light brown; inner bud membrane yellow-green. Leaf: 5 x 3 mm triangle, reddish. Flower buds positioned on the upper 0.50-0.6 m of the stem, leaf below.

Inflorescence: 20 x 8-9 mm, round or ovoid, light gray, nappy (hair in all directions), long not shiny; flower bracts with black tips, 3-5 green leaves, densely pubescent outside, surround the inflorescence. Lower inflorescences occasionally in clusters of three with one big in the middle and two smaller ones on the sides. Catkins almost adhere to the stem. Anthers red, but mature yellow.

Native habitat: Eurasia: Turkey, Armenia, Iran.

Hardiness: Zone 5-7.

Phenology: Losing most of bud scale at the beginning of February, during the middle of February the catkins reach maximum size; anthesis at the end of February.

Notes for catkins production: Catkins are very prolific and dense (8-9 per 10 cm). The earliest species to bloom (after *S. schwerinii*). Differs from other species by its green leaves at the base of inflorescence.

Salix amplexicaulis Bory

Size: 2-4 m high and wide.

Stems: 0.7-0.8 m long; very thin, flexible; glabrous; gray-purple at the upper part, brown-purple at the base; small (15-20 mm) die back. Diameter 2 mm at the tip and 4-5 mm at the base.

Buds: Subopposite; flower 6x3 mm; bud scale dark red, leaf: 3x2 mm; scales orange.

Inflorescence: 10-12 x 4 mm; cylindrical; dark gray, not shiny (hair in all directions); adhere to the stem; flower bracts black; very small reddish leaves surround the inflorescence; occasional clustering of catkins.

Native habitat: Europe: Balkans, south of France.

Hardiness: Zone 5-7.

Phenology: Losing most of bud scale at the beginning of February, in mid- February the catkins reach maximum size; anthesis in the middle of March.

Notes for catkins production Catkins are not very prolific, occasionally interrupted by leaf buds, but sometimes dense (8-9 per 10 cm, or 4 pairs per 10 cm). Immature catkins are of only moderate interest, but visual interest increases during anthesis, when anther color ranges from deep red and orange to yellow.

Salix babylonica L.**'Tortuosa'** (syn. *S. matsudana* Koidz.'Tortuosa')

Common name: Corkscrew willow, Dragon's claw willow

Cultivar of Asian species (Far East of Russia, Northeast China, Korea, and North Japan) originated in Japan, where it is often found in the wild.

Size: 4-10 m high and 2-8 m wide.

Stems: 1.5-2.0 m long; curved or twisted; glabrous; olive-green to yellow, contorted and twisted. Diameter 3-5 mm at the tip and 7-10 at the base.

Hardiness: Zone 5-7.

Phenology: Losing bud scales in the middle of February; anthesis during the beginning of March.

Notes: Can be harvested anytime from November until March. Should be seasonally coppiced and kept as a shrub.

Salix caprea L.

Common name: Goat willow; Pussy Willow.

Size: 6-10 m high and 2-5 m wide.

Stems: 1.5-2 m, straight, slightly curved; stiff, pubescent, base glabrous; purple-brown or green. Diameter 3-4 mm at the tip and 8-10 mm at the base, or even thicker on stronger shoots.

Buds: Flower: 10 x 5 mm long, conical, purple-brown, glabrous or pubescent; leaf: 4x2 mm reddish-green. Flower buds on the upper 0.60-0.9 m of the stem.

Inflorescence: 15 x 8 mm, ovoid; light gray; some shiny; black flower bracts; 3 small rudimentary leaves surround the inflorescence; inflorescence directed at acute (15^o) angle to stem axis; anthers yellow.

Native habitat: Europe, west Asia.

Hardiness: Zone 4-6.

Phenology: Losing most of bud scale at the end of February; reaches maximum size in mid-March; anthesis in the middle of April.

Notes for catkins production: Catkins are very prolific and dense (8 per 10 cm). Ornamental at different stages: through winter as brown twigs with prominent stout buds; at the initial stage of bud scale break, and after losing bud scales. Typically *S. caprea* does not propagate well by cuttings, but a few clones have been selected which root easily. Some hybrids of *S. caprea* appear in trade as *S. discolor*. *Salix cinerea* (Gray willow) has similar stem and bud structure, but develops and can be harvested a few weeks later.

Salix discolor Muhlenb.

Common name: Pussy willow.

Size: 2-4 m high (up to 7 m in wild) and 1-2 m wide.

Stems: 0.7-1 m long; not flexible; tip pubescent, base glabrous; gray-brown or purple-brown. Diameter 2 mm at the tip and 5-7 mm at the base.

Buds: Flower: 10 x 4 mm, ovoid; deep brown, glabrous; leaf: 4 x 2 mm conical. Bud scale is red or brown.

Inflorescence: Size 10-12x5-6 mm, ovoid, gray, some shiny; flower bracts with black tips.

Native habitat: North America.

Hardiness: Zone 2-6.

Phenology: Losing bud scales at the end of February, anthesis at the end of March.

Notes for catkins production: Catkins are not prolific and their arrangement is irregular (often interrupted by leaf buds). Inflorescences are larger than any native eastern North American species, but other described species are superior. During last few years cut stems of this species were introduced into trade. Hybrids with *S. caprea* are occasionally grown under this incorrect name.

Salix gracilistyla Miq.

Size: 2-3 m high and 1.5 m wide.

Stems: 1.5-1.8 m, arching; stiff, pubescent or glabrous; purple-brown and puberulent at the tip, base green and glabrous; die back minute. Diameter 3-4 mm at the tip and 8-10 mm at the base, or even thicker on stronger shoots.

Buds: Flower: 12-17 x 7-8 mm, conical with broad base, chocolate brown or bronze-brown, puberulent; very prominent; leaf: 3-5 x 3-4 mm gray or purple, pubescent. Leaf buds are located only on the lower 30-60 cm part of stem.

Inflorescence: 25-35 x 10-15 mm, ovoid; light gray, shiny; flower bracts almost black at the tip, pink at the bottom, much shorter (2-2.5 times) than surrounding hairs, so the catkins are very soft; 1- 3 rudimentary leaves surround the inflorescence; occasional clustering of lower inflorescence; inflorescence directed at acute (25-45^{o}) angle to stem axis; anthers yellow.

Native habitat*:* Asia: Japan, Korea, and China.

Hardiness: Zone 5-7.

Phenology: Losing most of bud scale at the beginning of February, during the middle of February the catkins reach maximum size; anthesis during the middle of March.

Notes for catkins production: One of the best species for cut stem production. Catkins are very prolific and dense (7-9 per 10 cm). Dries very well and can be used for arrangements for years.

'Melanostachys' (*S. gracilistyla* var.*melanostachys* Schneid., *S. melanostachys* Mak., S. 'Kurome' Hort.,).

Male cultivar of *S. gracilistyla* with purple glabrous stems and black catkins. Inflorescence cylindrical, shiny, 15-20x 6-8mm, with dark brown or black glabrous flower bracts (occasionally red at the base); surrounded by 3 small green leaves.

The phenological development about 1 week later than the species. Anthers brick-red becoming yellow. Catkins are not prolific and their arrangement is irregular. Usually 3-5 flower buds at the upper portion of the stem. North of Zone 6 is less vigorous.

A very unusual and attractive cultivar originating in Japan. S. 'Kurome' means black (kuro) bud (me). It was introduced to USA through W.Hoogendoorn & Son Nursery, Boskoop, Netherlands.

'Hagensis' (*S. hagensis*, S. 'The Hague', probably a hybrid of *S. gracilistyla* and *S. caprea*).

Size: 2-3 m high and 1.5-2 m wide.

Stems: 1-1.2 m; straight, slightly curved, rigid. Diameter 3 mm at the tip and 5-8 mm at the base.

Buds: 15 x 7 mm; bronze, dark brown, very prominent before opening.

Inflorescence: Catkins up to 5 cm light-gray. Flower bracts are pink with black tips with very long hair, very soft.

Hardiness: Zone 4-6.

Phenology: Losing flower scale in the middle of February; anthesis in the middle of March.

Notes for catkins production: Female cultivar with big inflorescences, especially clustered on the upper portion (20-30 cm) of the stem, prolific and dense (10-12 per 10 cm); produce numerous aberrations. Developing about one week later than *S. gracilistyla*. Vigorous shrub.

S. hookeriana Barratt.

Size: 1-3 m high and wide.

Stems: 0.6-0.8 m; densely pubescent olive-green at the tip, green glabrous at the base. Diameter 3 mm at the tip, 8-10 mm at the base.

Buds: Flower: 10 x 6 mm, glabrous, brown or red-brown; leaf: 3 x 2 mm, orange-brown. A few leaf buds at the tip, than 7-10 flower buds (30-40 cm).

Inflorescence: Male: 30-40 x 10-15 mm; thick; not shiny (nappy); ovoid; anthers yellow; female 40-60 x 15 mm.

Native habitat: Western North America.

Hardiness: Zone 4-6.

Phenology: Bud break during the middle of March; anthesis starts in mid- April.

Notes for catkin production: Catkin density 3 per 10 cm. Woolly catkins can be harvested at the same time as *S. discolor*. Due to late blooming time and almost white large catkins, this species is excellent for stem production.

Salix humilis Marsh.

Common name: Prairie willow

Size: 1-2 m high and wide.

Stems: 1.2-1.5 m long; straight, slightly curved, flexible; densely pubescent brown-gray at the tip, base glabrous green. Diameter 1.5-2 mm at the tip, 5-7 mm at the base.

Buds: Flower: 6 x 3 mm, broad conical, brown-gray, pubescent; leaf: 3 x 2 mm, purple-gray, located on the lower 20 cm of the stem.

Inflorescence: 10 x 4 mm, ovoid or round; dark gray, not shiny; anthers brick-red later turning yellow, ovary yellow with brick-red stigmas.

Native habitat: Northeast North America.

Hardiness: Zone 4-6.

Phenology: Losing bud scales at the end of March; anthesis at the beginning of April (coincides with the beginning of flowering of *Amelanchier arborea*, *Cercis canadensis* and *Cornus florida*)

Notes for catkins production: Along with *S. schwerinii*, has the smallest catkins, but blooms much later. Catkins are very abundant and dense (14 per 10 cm).

Salix koriyanagi Kimura (*S. purpurea* var. *japonica* Nakai)

Size: 2-4 m high and 1-2 m wide.

Stems: 1.2-1.5 m long; straight or slightly curved, flexible, delicate; yellow-brown or olive-brown; glabrous. Diameter 1.5 mm at the tip and 4 mm at the base.

Buds: Flower: 6 x 2 mm long, light brown, conical; alternate or subopposite. Leaf: 1.5 x 3 mm, reddish. Position of flower and leaf buds: 5-8 cm from the tip leaf bud, then flower.

Inflorescence: Male: 20-22 x 4-5 mm long, cylindrical, very dark gray, not shiny, hair are multidirectional; bracts almost black with occasional pink, pubescent; inflorescence directed at acute (25-30^{o}) angle to stem axis; 2-3 leaves the same color as bracts surround the inflorescence; stamens deep red then yellow. Female: 12 x 3 mm; thinner and lighter gray-pink; cylindrical.

Native habitat: Korea; widely cultivated in Japan for basket rods.

Hardiness: Zone 5-7.

Phenology: Losing bud scales at the beginning of February; at this time the catkins are purplish; as they develop and reach their maximum size male inflorescences turn dark gray or almost black while females remain purple; anthesis during the middle of March.

Notes for catkins production Catkins are very prolific and dense: 20-22 or ten pairs per 10 cm. Prolonged harvesting time lasts several weeks. Most male specimens we observed had the catkins, which dried after reaching its maximum size, but before anthesis. Benefits from coppicing to one-third of its height. Male specimens were received as *S. gilgiana*.

Female specimens are grown in trade under the name *S. koriyanagi* ‘Rubykins’.

S. kuznetzowii Laksch.

Size: 2-3 m high and 1-1.5 m wide.

Stems: 1.2-1.5 m long; straight; rigid; olive-green, puberulent, base green glabrous. Diameter 3 mm at the tip and 10-12 mm at the base.

Buds: Flower: 10 x 5 mm, conical with attenuate tip, chocolate brown, puberulent; leaf: 4x2 mm, triangular yellow-green.

Inflorescence: 25 x 12 mm; ovoid with wide base; anthers yellow.

Native habitat: Europe: Caucasus.

Hardiness: Zone 3-6.

Phenology: Bud break during the middle of March; anthesis during the beginning of April.

Notes for catkin production: This species can be used for twig production. Flower buds are stout and prolific with density is 6 per 10 cm.

Salix miyabeana Seemen

Common name: Miyabe willow

Size: 3-6 m high and 1.5-2 m wide.

Stems: 1-2 m long, straight or slightly curved, wavy in the middle; not flexible; glabrous; gray or brown. Diameter 3 mm at the tip 15-40 mm at the base.

Buds: Flower: 10-12 x 5 mm, conical, light brown, adheres to the stem; leaf: 5 x 2mm, red.

Flowers located on the upper 60 cm of the stem, occasionally interrupted by a few leaf buds.

Inflorescence: Female: 50 x 6-8 mm; light green, whitish at the end; lax; cylindric; not shiny; flower bracts green with purple or black tip, lightly pubescent, 3 small green leaves surround the inflorescence. Catkins resemble a snake’s tail when young, and a bottle brush when mature. Male 30-50 x 10mm; anthers yellow.

Native habitat: Asia: Japan, Korea, North China.

Hardiness: Zone 5-7.

Phenology: Losing bud scales at the beginning of February, but the catkins remain small for a while; reach maximum size at the beginning of March; anthesis in the middle of March.

Notes for catkin production: Only female stems have an interest for floral branches. Catkins are prolific and dense (8-10 per 10 cm). After coppicing, produces straight stems 3-3.5 m tall and can be used in very large arrangements. It does not have effect of fuzziness, since flower bract pubescence is very scarce.

Salix schwerinii Wolf

Size: 2-3 m high and 1.5-2 m wide; up to 10 m in native habitats.

Stems: 0.6-0.8 m; straight, slightly curved, delicate, but not very flexible; die back 0.3-1 cm; dark purple-brown slightly pubescent at upper part, brown-green glossy at the base. Diameter 2 mm at the tip and 6-8 mm at the base.

Buds: Flower: 6 x 3, narrow conical, brown, slightly pubescent; leaf: 4 x 2 mm, triangular, color as stem.

Inflorescence: 10-12 x 4-5 mm, round, dark gray, shiny; located at acute (30^{o}) angle to stem axis; flower bracts black; only females have been observed.

Native habitat: Asia: Far East of Russia, North-East of China, Korea, and Japan.

Hardiness: Zone 4-6.

Phenology: Start losing flower scales in December; should be harvested quickly at the end of January since catkins lose ornamentality and stigmas became visible (gray catkins have yellow-green tint) as soon as it reaches its maximum size.

Notes for catkin production: Catkins are very prolific and dense (12-16 per 10 cm). The first species to develop in early spring; it has the smallest catkins of all species, very abundant, and good for filler in spring bouquets.

Salix udensis Trautv. **'Sekka'** (*S. sachalinensis* Schmidt 'Sekka', S.'Setsuka')

Common name: Japanese fan-tail willow

Cultivar of Asian species (Far East of Russia, Northeast China, Korea, and North Japan) originated in Japan, where it is often found in the wild.

Size: 2-3 m high and wide; in native habitats up to 30 m.

Stems: 1.5-2.0 m long; curved or twisted, fascinated and flattened, very rigid; glabrous; mahogany or chestnut brown. Diameter 5-50 mm at the tip and 10-15 at the base,

Buds: Flower 7 x 3mm, narrow cylindrical with blunt tip, purple brown; when losing the bud scales, sometimes lower portion of the bud remains around the inflorescence: leaf: 3 x 4, purple-red. Flower buds on the upper 60 cm of the stem.

Inflorescence: 15 x 5 mm, cylindrical, light gray, shiny; male cultivar; anthers yellow.

Hardiness: Zone 5-7.

Phenology: Losing bud scales in the middle of February; anthesis during the beginning of March.

Notes: Can be harvested anytime from November until March, but it is most ornamental while losing bud scales. Benefits from coppicing down to 1/3 or 2/3 of stems. Leafy branches can also be used for large arrangements. Occasionally retains10-15% of last year's foliage until spring; unflattened branches are also attractive for dense catkins and chestnut color. Introduced to USA through W.Hoogendoorn & Son Nursery, Boskoop, Netherlands.

S. x***friesiana*** Anderss.

Hybrid (*S. viminalis* x *S. repens*), originally found in Scotland and later in other European countries.

Size: 0.5-2 m tall and wide.

Stems: 0.3-0.5 m long; slightly curved, flexible, purple-brown puberulent at the tip, green and glabrous at the base. Diameter: 1mm at the tip and 4 mm at the base.

Buds: Flower: 6-8 x 4 mm, ovoid with narrow tip; dark-purple or purple-brown puberulent; located at acute (30^o) angle to stem axis; leaf 3 x 2mm light brown; triangular. A few leaf buds at the tip, then 7-10 flower, than leaf at the base.

Inflorescence: 15-30 x 5-7mm; light gray; shiny; male; anthers yellow.

Hardiness: Zone 4-6.

Phenology: By the middle of March is losing bud scales and reveals catkins; flowers during the middle of April.

Notes for catkin production: Stems are not long and can be used for small arrangements. Catkin density 10-13 per 0.1 m.

S. x***multinervis*** Doell.

Hybrid (*S. cinerea* x *S. aurita*), occurring throughout Europe.

Size: 2-4 m tall and 1.5-2 m wide.

Stems: 1-1.2 m long; slightly curved, flexible; gray-green.

Diameter 1-1.5 mm at the tip and 6-7 mm at the base.

Buds: Flower: 10 x 5 mm, bright red; located at acute (30^{o}) angle to stem axis; leaf: 3x1.5mm light brown.

Inflorescence: 30 x 6 mm; female; narrow cylindrical shape with 4 densely pubescent leaflets at base.

Hardiness: Zone 4-7.

Phenology: Late development: bud break at the beginning of April; anthesis during the middle of April.

Notes for catkin production: Not superior for cut stem effect, but the latest to develop. Flower bud density 5-6 per 10 cm; catkins born all along the stem; very similar to *S.* x*wimmeriana*, but develops later.

Salix x***tsugaluensis*** Koidz. **'Ginme'**

Hybrid species (*S. integra* x *S. vulpina*) occur in Japan in the wild. 'Ginme' is a female clone.

Size: 2 m tall and wide, widely spreading.

Stems: 1.2-1.5 m long; straight or slightly curved, rigid, glabrous, shiny; olive-green, base light green. Diameter 2 mm at the tip, 13-15mm at the base.
Buds: Flower: 10-12 x 3-4 mm, narrow conical, bright red with yellowish tips; adhere to the stem before bud breaking; leaf: 3 x 2 mm, triangular, red; leaf buds on the lower 30-50 cm of the stem.
Inflorescence: 20 x 5 mm; cylindrical; slender and recurved; silvery, shiny; surrounded with a few green leaves; some catkins in clusters.
Hardiness: Zone 5-7.
Phenology: Bud break begins during the end of February; anthesis during the beginning of April.
Notes for florists: Flower bud density 12-16 per 10 cm, appearing all along the stems. Ornamental for its bright bud scales, and can be harvested from November until February, before or after bud break, but before anthesis. Dry stems retain color. It was introduced to USA through W.Hoogendoorn & Son Nursery, Boskoop, Netherlands. The cultivar name is derived from Japanese "gin"(silver) and "me" (bud).

Salix x***wimmeriana*** Gren.&Godr.

Hybrid species (*S. caprea* x *S. purpurea*), occurring with the parents in the wild.
Size: 2-4 m high and wide; sprawling at the base.
Stems: 1.5-1.8 m long; straight, slender, slightly zig-zag; glabrous; purple-brown or gray-brown. Diameter 2 mm at the tip, 8-10 mm at the base.
Buds: Flower: 10 x 5 mm, conical, red-purple, adheres to stem; flower buds located on the upper 1.20 m; leaf 5 x 3 mm, triangular.
Inflorescence: 10-15 x 5-7 mm; ovoid; light gray, shiny; male; anthers brick red turning yellow.
Hardiness: Zone 4-7.
Phenology: Bud break begins early March; anthesis in the beginning of April.

Notes for catkin production: Flower bud density 7-8 per 10 cm; catkins born all along the stem; interesting by its purple twigs with bright red prominent buds (but overall appearance darker than *S. xtsugaluensis* ‘Ginme’); can be harvested from November until March before or after bud break, but before anthesis.

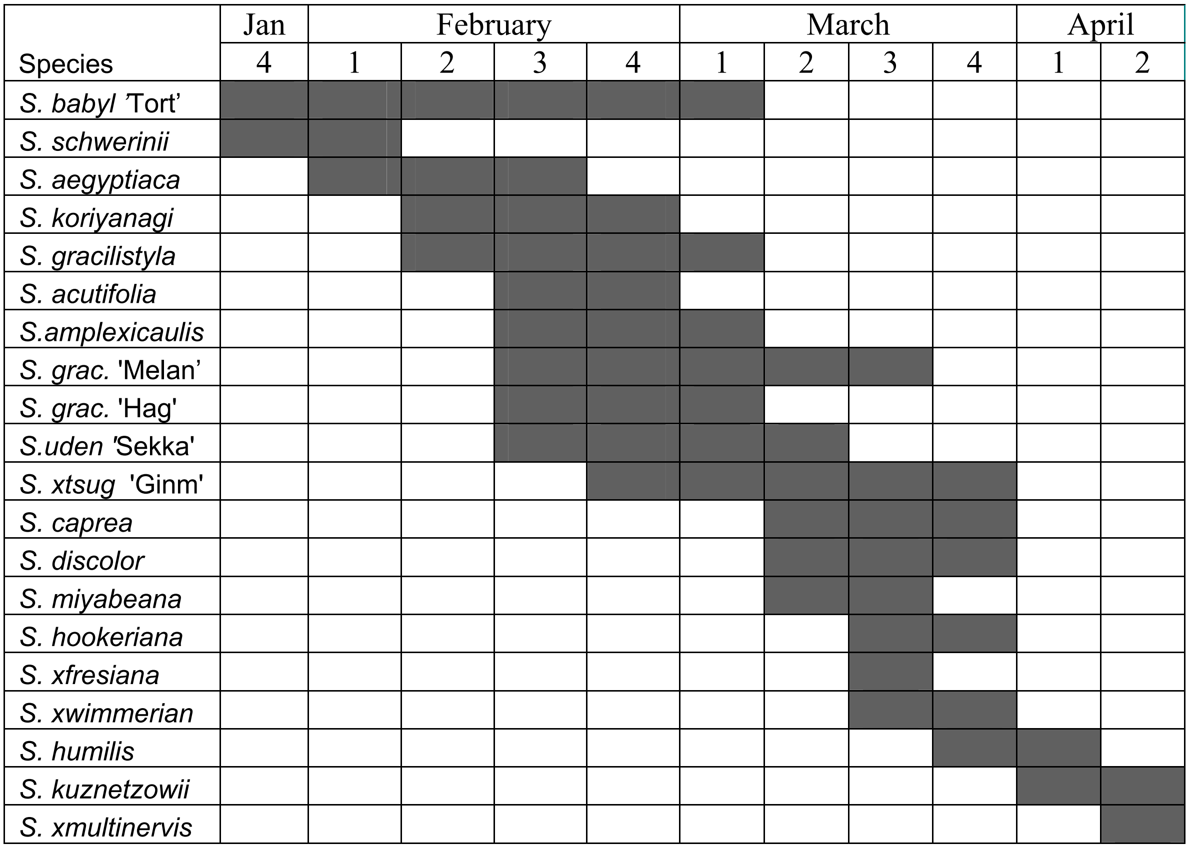


Figure 5.1. Approximate schedule of *Salix* stem harvesting in central Ohio (latitude 40^o north) showing the extensive period that can be achieved by using an assortment of species. For those species meant for twig production (stems ornamental before bud break) harvest time can be extended throughout dormant period from November until March. Annual weather fluctuation may affect actual dates in a given area, but progressive sequencing of phenological events between species will remain constant. For phenological orientation in zones 4/5 and adjustment for other regions, several indicator species can be used: the second week of March (Mr2) corresponds to the beginning of *Cornus mas* flowering, the third week of March (Mr3) corresponds to the beginning of *Forsythia* flowering and the second week of April (Apr2) to the beginning of flowering of *Cornus florida*, *Amelanchier arborea* and *Cercis canadensis*.

CHAPTER 6

ORNAMENTAL WILLOWS (*SALIX* L.) FOR ALPINE AND SMALL URBAN GARDENS

Introduction

Due to their small mature size and wide ecological adaptability, low-growing and dwarf *Salix* species can be successfully used in small urban spaces, as well as in residential rock and alpine gardens. Medium size shrub willows, those 0.5 to 1.5 m (1.5 to 5.0 ft) are also suitable for limited space in confined urban gardens. Nowadays willows occupy an insignificant place in most nursery stocks, despite their variability and hardiness. The horticultural literature on *Salix* is very scarce and descriptions and performance information are not reliable for many species. Good photographic images of many species are difficult to find.

The small willows described here represent low-growing species of temperate zones as well as arctic and alpine species. Our purpose is to evaluate an array of obscure species available either in the trade or from public and private collections, particularly those in Great Britain and Eastern Europe. We assess their ornamental potential for small garden landscape, assess their performance in the continental conditions of the Midwestern U.S., and verify identification and clarify taxonomy at the level of species and cultivar. The present work represents a distillation of literature searches in *Salix* nomenclature—for North America, Europe and Asia, and includes three years of growth data and evationalu of these species in central Ohio (USDA hardiness zones 4/5). Most of the taxa discussed here include species that are not well known and have only limited availability. We provide descriptions of each species with proposed correct names.

Our hope is to reveal the horticultural potential of under-used small shrub willows. Many attractive species are still unknown to horticulturists and the general public, and some are not available through public collections anywhere. We hope to publicize new willow introductions and to correct some current errors in species and cultivar names.

Materials and methods

Between 1999 and 2002 we collected or received approximately 200 willow specimens from American and European (British, Polish, and Russian) nurseries, botanical gardens and arboreta. These plants were installed in replicated plots at the Ohio State University Chadwick Arboretum and the Waterman Agricultural Research Facility, both in Columbus, Ohio. Performance data were collected over three growing seasons. Plants received supplemental water during the first year after planting to assist them to establish root systems, but were not subsequently irrigated. These *Salix* taxa have been under observation throughout the period of study. The sixty species and cultivars described here have been selected for their relatively low growth habit. The field performance evaluations included growth rates and ornamental qualities, as well as insect and disease resistance, and drought, heat and cold hardiness.

The greatest challenge was the identification of species since many specimens were misnamed at the germplasm source. In an attempt to clean up some long-standing inaccuracies in *Salix* taxonomy, we turned to original authorities on nomenclature, including Skvortsov (1968) in Russia, Argus (1997) in Canada and Krussmann (1985) in Germany. In the nursery trade, we hope that all effort will be made to discontinue the use of invalid or improperly cited names.

Systematics

The genus *Salix* consists of 3 subgenera. The tree-type species belong to the subgenus *Salix*, the shrub-type to the subgenus *Vetrix* Dum., and the most low growing and prostrate species to the subgenus *Chamaetia* Nasarov (Skvortsov (1968)). All species examined here are included in the subgenera *Chamaetia* or *Vetrix* (Table 6.1).

The subgenus *Chamaetia* consists of five sections: *Chamaetia* Dum., *Retusae* Kerner, *Myrtilloides* Koehne, *Glaucae* Pax and *Myrtosalix* Kerner. The subgenus is especially rich in dwarf and low-growing or creeping species; many of them are true alpine and arctic species. The members of this subgenus are typically well adapted to the extreme conditions of montane highlands and tundra. Low-growing and prostrate species can be found in a few other sections of the subgenus *Vetrix*. Representatives of sections *Arbuscella* Seringe, *Glabrella* Skv., *Hastatae* Kerner, *Helix* Dum., *Incubaceae* Kerer, *Lanatae* Koehne, *Vetrix* Dum., *Villosae* Rouy and *Candidae* Schneider are described, as well as hybrid species that crosses section divisions.

Environmental adaptations of arctic and alpine *Salix*

Many species described here originate in arctic tundra or alpine and subalpine zones of the Northern hemisphere, areas lying above latitudinal and altitudinal tree-lines. Some high alpine areas are even named "zones of dwarf willows" because they are the dominant or the only woody species surviving in this extreme environment.

The natural habitats of alpine and arctic species possess unique temperature, light regimes and soil conditions. The tundra is characterized by permafrost: frozen, poorly drained subsoils with a very limited topsoil layer active only in summer, slow rates of decomposition and nutrient cycling, and extremes of photoperiodicity with very long days during summer months and almost complete darkness in winter. In alpine zones, plants often grow on exposed rocks or gravelly slopes with little organic soil, constant physical disturbances caused by strong wind and erosion, and intense solar radiation. The strong ultra-violet light of high mountain areas has a stunting effect on plant growth and produce forms of dwarfing. Conditions are normally arid due to radiation and strong winds drying the soil, and available moisture is confined to fast running drainages along rocky slopes. Both arctic and alpine regions are characterized by a short vegetative season, in some areas lasting only 6 weeks, extreme diurnal temperature fluctuation, low temperatures in winter, and poorly developed soils.

To survive in these conditions organisms must be highly adapted to the ecosystem. Alpine and arctic plants have developed a number of morphological and physiological adaptations enabling them to perfectly fit into this environment and function and reproduce successfully.

Arctic and alpine willows grown under severe conditions are much smaller and they don't possess the vigor of their lowland relatives. Many of them exhibit a completely prostrate habit, with their stems and leaves lying parallel to the ground while burying the apical meristems below the soil surface or under the snow. Compact carpet or cushion habit create microclimates that help to protect the apical meristems against thermal fluctuations and enhances shoot hydration, thereby decreasing susceptibility to winter and storm damage. Small leaves prevent excessive water loss through transpiration. Most arctic and alpine willow species have a typical dichotomy in bud size, in which the uppermost 3-6 buds on the stem are larger than the rest. These large buds produce generative as well as vegetative shoots. Smaller buds will not open in spring but can be broken from dormancy by unusual environmental conditions; they serve as "insurance" for survival in extreme situations.

The alpine-subalpine species may spend 7-9 months of the year under snow, after which their entire reproductive cycle must be completed within a few months or less. Their phenology is adjusted for growth in short vegetative seasons and they start to grow as soon as the snow disappears. For example, *S. herbacea* (Dwarf willow) needs only 2-3 months to grow and complete its reproductive cycle. The developmental patterns of shoot development among arctic, alpine and lowland species are very different. *Free growth* (the initiation and elongation of stem units proceed simultaneously (Lanner, 1976)) is typical for lowland species and favored by mild conditions. In contrast, predetermined or *fixed growth* (a dormant period intervenes between the initiation and elongation of stem units) occurs under severe environmental conditions with a short vegetative season. *Fixed growth* results in a limited quantity of leaves and cessation of growth in early summer. The smallest species will develop only 2-5 leaves per stem (*S. herbacea*), others up to 15-20 leaves (e.g., *S. alatavica*, *S. reinii*), but all leaves are preformed in the buds during the previous fall and in spring they just unfold from the bud.

Other features such as small leathery leaves, reduction of trunk size and exposure (sometimes stems are located entirely in the substrate, leaving only leaves and catkins on the surface) contribute to species adaptability. Optical properties such as reflectivity of pubescent buds, leaves, stems and flowers (flower bract and ovary) are typical morphological adaptations of tundra species, helping to modulate daily temperature fluctuations and to reflect radiation, preventing tissue overheating.

For most species, flowering takes place at the same time as the leaves are unfolding. The erect catkins of alpine and tundra species are usually not very abundant and are located just below the tip of the previous year's shoots. The inflorescences emerge from preformed flower buds, thus maximizing time for flowering and seed set during the short summer. Typically, anthers of filaments of arctic and alpine species are bright red or purple to attract insect pollinators more effectively.

Cultural requirements

Willow shrubs, in spite of their general adaptability, will reliably establish themselves and retain their characteristic forms only under specific conditions. An understanding of the natural environment in which wild alpine *Salix* species live is essential for their successful cultivation. They grow in open places with maximum exposure, and where there is little interspecific competiton. High light requirements can be easily met if plants are installed on raised, totally exposed beds or on terraced slopes. There is no need for alpine houses or scree beds to cultivate willows, as required for many other alpine plants. Willows thrive in small pockets of leaf mold or other moisture-retentive yet well drained organic soil. The use of young pot-grown plants with a good root system will improve plant establishment. Mulching, either with organic or nonorganic materials (rocks or pebbles) will benefit species with shallow, widely spreading root systems.

There is evidence that some species prefer specific soil pH ranges in their regions of origin. Some of them (*S. alpina*, *S. elaeagnos*, *S. reticulata*, *S. retusa*, *S. saxatilis*, *S. tarraconensis*) prefer more basic substrate, while others (*S. herbacea*, *S. glauca*, *S.helvetica*) prefer acid soils. However, we grew our test species in a variety of soils and they all appear to be pH adaptable.

While tolerant of a wide range of soil conditions, most willows also do not require proximity to standing water or a high subterranean water table. The imitation of swamp or bog environment for species typically inhabiting such areas appears not to be necessary. Perhaps it is only in natural low-lying or more temperate ecosystems that in extremely moist conditions willows can avoid competition. For example, *S. lapponum*, *S. rosmarinifolia*, *S. cinerea* and *S. pedicellaris* are often found growing in saturated ground, but they grew even better in well-drained soil at the collection site. Some species (*S. repens*, *S. purpurea*) can flourish in dry sandy soil. Of major importance in garden culture is to help plants get established during early stages of root system formation; later they should be able to tolerate some periods of drought. Only a combination of hot weather (above 90°F) for prolonged periods, drought and compacted soils (considered to be too dry because of insufficient pore space to hold water) appears to be detrimental for some alpines with superficial root systems. During periods of drought, plants would require supplemental watering as in any installed landscape.

Willows benefit significantly from occasional pruning, to prevent unkempt appearance and to stimulate new growth, especially as plants become older. All species except *S. variegata* have their flower buds located on branches formed the preceding year, so the best time to prune is in early spring or right after flowering (for precocious species). Beause the ultimate size of many willows can be limited by coppicing, some naturally large-growing but ornamentally valuable willows such as *S. elaeagnos* can be incorporated into the small garden.

Different crown forms, including weeping, contorted, or arching habits, can be achieved by grafting. Several rootstocks, such as *S.* x*smithiana*, the hybrid of *S. caprea* and *S. viminalis*, are very compatible with many species of ornamental top-graft stock. The most popular grafted cultivars in USA are *S. caprea*'Pendula' (Weeping pussy-willow), and *S. integra* 'Hakuro-Nishiki' (Dappled willow). But many other willows having naturally creeping growth can be grafted onto strong-growing upright willows of variable height, usually from 30 to 170 cm **(**1.0 to 5.7 ft) (Marczynski, 1998).

The phenology, certain morphological features, such as dwarfing, and physiological traits such as fixed growth, appear to be under genetic but not environmental control. Species from high attitudes and latitudes continue to follow seasonal patterns similar to the patterns in their natural regions: late bud break and blossom time in spring, annual defoliation a few weeks or even months earlier than locally adapted species, and prolonged dormancy, up to 7 months for some species. Most arctic and alpine species develop only one generation of new shoots per year, but a few under favorable conditions can have several flushes of growth (elongation of more than one terminal bud per shoot each year).

Phenology

Willow phenology is typically as much as four to six weeks ahead of other woody plants in a given area. They break bud in very early spring, and most willow species bloom and foliate before other woody plants even begin to emerge. Willows often provide the most important early pollen source for bees and other insects. By very early summer (early June) many arctic and alpine willows cease all shoot growth, by late summer leaf senescence has begun, and in September-October they shed foliage.

While the precise timing of phenological development fluctuates from year to year depending on weather conditions, the sequence of the events is consistent. In central Ohio, the first species to leaf out at the end of March is *S. variegata*, followed a week later by *S. brachycarpa* 'Blue Fox", *S. crenata*, *S. retusa* and *S. serpyllifolia*. At this time *S.* x*friesiana* starts blooming, *S. caprea* 'Pendula' and *S. rosmarinifolia* are in full bloom, while other species are only breaking their flower bud scales (*S.* x*balfourii*, *S. subopposita*). Closer to the middle of April more species break their leaf buds and start flowering: *S. helvetica*, *S. integra*, *S. islandica*, *S.* x*grahamii*, *S. repens* and *S. purpurea* (which blooms at the same time as leafing). One week later (the second to third week of April) *S. alatavica*, *S. alpina*, *S. arbuscula*, *S.* x*balfourii* are in full bloom, while other species are already fully foliated (*S. brachycarpa*, *S. brevipens*, *S. crenata*, *S.* x*doniana*, *S.* x*gillotii*, *S. glauca*, *S. reinii*, *S. repens* 'Iona', *S. tarraconensis*). At the end of April *S.* x*ambigua*, and *S. helvetica* are in blossom and at this time the late species start to foliate (including *S. coesia*, *S. lanata*, *S. lapponum*, *S. nakamurana*, *S. pyrenaica* and *S. purpurea* 'Pendula'). An appropriate planting of species and cultivars in sequence with one another can provide a long blooming time in the spring garden.

Ornamental features and uses of low growing willows

Low growing *Salix* species are versatile enough for numerous ornamental applications. They are not "utilitarian shrubs" as are their lowland relatives (for instance the large species used for embankment or riparian stabilization), but rather a specialty plant material.

The principal and most recognizable features of willows are their infloresences, or catkins. Willows are dioecious, and in general male plants have showier and more attractive inflorescences than females. However, some species also have attractive female inflorescences (*S. pyrenaica*, *S. variegata*).

Many small willows exhibit ornamental qualities year round. The texture of foliage canopies ranges from very fine (*S. purpurea*) to coarse (*S. alatavica*, *S. reinii*). Many species can be grown for their foliage (rather than for spring flowering) and with their early leaf break they provide the first green color in the spring landscape. In summer, dark green, blue, yellow-green, gray or intense silvery foliage provide effective contrasts to other plants. Many species retain clean leaves throughout the season, though a few begin to yellow or spot by summer's end.

Even leafless shrubs with bare stems and varying forms of ascending or pendulous habit can add interesting architecture to the garden and contribute substantially to the character and appearance of the rock garden. The potential role of willows in the rock garden has been underestimated: typically, garden books about alpines list no more than 2-3 willow species. Prostrate species are ideal for cascading over a wall or to cover the edges. Small upright shrubs can make excellent specimen plants, acting as a centerpiece around which the herbaceous composition can be developed. "Alpine looking" foliage is a major asset of some species such as *S.* x*balfourii*, *S. helvetica* and *S. lanata*. Interesting crown architecture when specimens are only a few years old can impart an ancient or gnarled look, adding a sense of maturity to the young garden.

Low-growing willow species that grow rather too quickly for rock gardens can be used as accent plants for the perennial border. Many willows effectively combine with other plants as informal hedges, edging material or grouped for a mass effect. They can also be placed individually as specimens in lawns.

Cultivation of the smallest dwarf species requires special attention since the overshadowing by larger specimens and weeds could destroy the specimen. Many of them can be planted into troughs and other permanent containers to ensure their survival and improve display. Some truly dwarf species such as *S.* x*boydii*, *S. herbacea*, *S.*

lindleana and *S. reticulata* can be used as miniature plants in model railroad gardens. Medium sized willow species make complementary companions to *Calluna* and *Erica* in Heather gardens along with other low growing shrubs such as *Pinus mugo* and *Betula nana*. Slow-growing alpine species are also commonly trained as bonsai (*S. repens*, *S. helvetica*). Those species also having attractive catkins are effective specimens for early spring exhibition.

Future introductions

The use of willows in the North American market, and particularly the continental Midwest, can be further extended through introductions of native shrubs to the nursery trade. The potential for development of New World willow species is underscored by the fact that the most of species now used ornamentally have Eurasian origin, and some of them have circumpolar distribution (*S. arctica*, *S. glauca*, *S. herbacea*, *S. polaris* and *S. reticulata*). Only two North American endemic species (*S. brachycarpa* and *S. candida*) are currently in popular cultivation.

The subgenus *Chamaetia* should be a focus for research and many North American representatives should be evaluated for ornamental introduction These include *S. nivalis* Hook., *S. vestita* Pursh (Sect. *Chamaetia* Dumort.), *S. setchelliana* C.R.Ball (Sect. *Setchellianae* Argus), *S. nummularia* Andersson (Sect. *Herbella* Ser.), *S. arctophila* Heller, *S. chamissonis* Andersson, *S. fuscescens* Andersson, *S. phlebophylla* Andersson, *S. polaris* Wahlenb., *S. rotundifolia* Trautv., *S. uva-ursi* Pursh (Sect. *Myrtosalix* Kerner), *S. jejuna* Fernald, *S. ovalifolia* Trautv., *S. stolonifera* Coville (Sect.

Ovalifoliae Schneider), *S. cascadensis* Cockerell, *S.petrophila* Rydb., *S.sphenophylla* Skvortsov (Sect. *Diplodictyae* Schneider), *S.athabascensis* Raup, *S. chlorolepis* Fernald, *S. raupii* Argus (Sect. *Myrtilloides* Andersson) and *S. niphoclada* Rydb. (Sect. *Glaucae* Adersson). Some members of other sections from subgenus *Vetrix* such as *S. hastata* L., *S. barclayi* Andersson and *S. commutata* Bebb (Sect. *Hastatae* Kerner), *S. arbusculoides* Andersson (Sect. *Arbuscella* Ser.) *S. alaxensis* Coville and *S. barrattiana* Hook. (Sect. *Villosae* Rouy) also merit further development for commercial introduction.

Additional Eurasian species belonging to the Subgenus *Chamaetia* and of interest for horticultural evaluation are: *S.* e*rythrocarpa* Kom. (Sect. *Chamaetia*), *S. nasarovii* Skv.,

S. turczaninowii Lakschewitz (Sect. *Retusae*), *S. myrtilloides* L. (Sect. *Myrtilloides*), *S. reptans* Rupr., *S. kurilensis* Koidz.(Sect.*Glaucae*), *S. berberifolia* Pall, *S. tschuktschorum* Skv., *S. myrsinites* L., *S. breviserrata* Flod., *S. rectijulis* Ledb. (Sect. *Myrtosalix*). Some interesting Eurasian species can also be found in the Subgenus *Vetrix*: *S. glabra* (Sect.*Glabrella*), *S. krylovii* Wolf (Sect. *Villosae*).

Great variation and polymorphism can be found in any native willow population, which has been a source of much confusion in *Salix* nomenclature. Therefore, for consistent performance in the trade it is important to use genetically identical plants and to select and propagate specific clones.

Conclusion

Tundra species are often difficult to cultivate in more southerly latitudes; certain factors such as length of vegetative period, photoperiod and irradiation are difficult to imitate and are serious considerations for plant establishment. However, in our trials in Columbus, OH *Salix* representatives of arctic, as well as alpine floras appear to be quite plastic and able to adapt to temperate conditions of the Midwest, where the milder winters and hot dry summer did not limit plant survival.

Introduction of alpine species to the North American Midwest will further ecophysiological research of the genus, and may provide useful data in the context of potential effects of climate change or global warming in arctic ecosystems.

Species description

The following list of descriptions should be regarded as preliminary. We hope, as other new information is published, that it will become more complete and any inaccuracies will be corrected.

Each species is discussed in a standard format:

Species: Scientific names are derived from Skvortsov (1968), Argus (1997) and the International Code for Nomenclature of Cultivated Plants (1995).

Common name: Given if published anywhere; most described species have no common name.

Habit: Described species have different growth habits: stems erect (shoots directed upward or multidirectional), prostrate (lying on the surface of the ground), decumbent (prostrate, but with erect or ascending tips), procumbent or trailing (prostrate but not rooting at the nodes), and repent or creeping (prostrate and rooting at the nodes).

Size: The mature size as published in literature sources and determined in field trials in central Ohio: dwarf (less 0.1 m), low (0.15-0.5 m), medium (0.6-2 m).

Stems: One year old stem thickness given as two measurements: at the top (below 4th bud) and at the base. Color of 1–2 year old shoots. For each species the variation of annual stem color at certain diapason is typical and the older shoots of most species have a grayish color.

Buds: Dimensions; length and width; shape and color.

Leaves: Dimensions; shape, apex, base, margin, color.

Flowers: Willows have one of three flower developmental patterns: precocious (flowers develop before the leaves), coetaneous (leaves and flowers develop at the same time), or serotinous (flowers develop after the leaves are fully developed). Male catkins fall soon after bloom, while female catkins stay on the tree until seeds ripen and disperse.

Native habitat: Continent and geographical region, based on literature sources.

Hardiness: Krussmann (1985) and Griffiths (1994) were consulted for hardiness, but their reliablity is questionable in some cases. Hardiness for Ohio is based on observations we have made over a three-year period. Generally most studied species can be considered as fully hardy in Ohio. The general problem with variegated cultivars (*S. integra* 'Hakuro-Nishiki' and *S. cinerea* 'Tricolor') include foliage fading or burning in the sun, but if used as understory plants they do not develop peak color performance. The most common fungal diseases of willows, observed in a few species in the trials, were rust and leaf spot.

Growth rate: Data based on our experience in Ohio. For species typically exhibiting fixed growth, cultivation had no apparent effect. Branches of these species do not exhibit the remarkable vigor typical of lowland willows, and generally the growth rates for arctic and alpine species very slow.

Phenology: Based on intensive observations over 3 years.

Landscape value: Possible uses and evaluation based on our observations.

Notes: Data on trade availability were taken from nursery catalogs and other published sources that were available to us.

Salix alatavica Kar.

Common name: Altai willow

Habit: Medium size upright shrub with stout short branches.

Size: 0.50-1.5 m high and 0.4-0.7 m wide.

Stems: Diameter 2-3mm at the tip and 6-7mm at the base, yellow-orange, glabrous; stiff.

Buds: Color same as stem; flower 5 x 3 mm ovate, blunt; leaf 2 x 1.5 mm triangular.

Leaves: 40x 15mm; leathery, glabrous; glossy dark green on the upper surface, glaucous underneath; acute apex, rounded base; prominent venation underneath; serrated margin; unfolding foliage reddish.

Flowers: Coetaneous; male catkins 20 x 8 mm, oblong with 3-4 small leaves at the base; flower bracts green with lighter beige tip; anthers yellow.

Native habitat: Asia. Subalpine and alpine regions of TianShan, Aerhtai Shan (Altai) and Sayan.

Hardiness: Zones 3-6.

Growth rate: Fast.

Phenology: Vegetative growth starts at the beginning of April and ends in early June; abundant flowers appear in the middle of April; in September some foliage gets brown but still nice foliar specimen until November.

Landscape value: Year round interest: vivid green color of foliage lasts until November, during dormant season ornamental by its stubby skeleton with bright orange-bronze buds and stems; tolerant of drought and compacted soils; interesting structural element for medium-size rock gardens; is closely related to *S. glauca* and is very similar in appearance.

Notes: Not available in the nursery trade.

Salix alpina Scop.

Common name: Alpine willow

Synonyms: *S. jacquinii* Host., *S. jacquiniana* Willd., *S. myrsinites* L. subsp. *alpina* Murr.

Habit: Low prostrate shrub with decumbent growth.

Size: 0.25-0.3 m high spreading to 0.4-0.5 m.

Stems: Diameter: 1mm at the tip and 3 mm at the base; dark purple, slender.

Buds: Color as stems; 3 x 2mm, conical.

Leaves: 20 x 15 mm; elliptic, rounded apex, cuneate base; almost entire margin; inconsistent yellow coloration in fall.

Flowers: Coetaneous; female catkins 15 x 5 mm on leafy peduncle; style 1mm long, stigma lobes 0.2-1 mm; mature capsules red-green.

Native habitat: Europe. Alpine and subalpine zones of Eastern Alps, Tatry, Carpathian Mts., Croatia and Macedonia. Almost always on limestone.

Hardiness: Zones 4-6.

Growth rate: Fast.

Phenology: Vegetative growth starts second week of April; flowers first and second week of April, abundant every year; capsules ripen at the end of April; later throughout the season producing scarce flowers on new stems; moderate yellow coloration in fall; at the end of summer lower leaves can be slightly affected by black spot.

Landscape value: Highly recommended, one of the best species for small rock gardens and containers; can be grafted on medium-size rootstock; ornamental from April till October with its ground-hugging habit and numerous reddish catkins (mature capsules resemble stars); fast establishing, disease and drought resistant.

Notes: Available in the nursery trade only in Europe.

Salix* x*ambigua Ehrh. (*S. aurita* L.x *S. repens* L.).

Habit: Medium size divaricate shrub.

Size: 1-1.5 m high and 0.5-1 m wide.

Stems: Diameter: 2 mm at the tip, 5 mm at the base; purple-brown, spreading; at first pubescent, later glabrous; grooved (as its parent *S. aurita*).

Buds: Flower: 5 x 3 mm conical, purple-gray; leaf 3 x 2 mm oblong; puberulent.

Leaves: 40 x 15 mm; narrowly elliptical; dark green above, gray densely pubescent beneath; acute apex, cuneate base; serrated margin; prominent venation underneath; persistent stipules.

Flowers: Precocious, later than most willows; female catkins15 x 6 mm, silvery, on long (12-15 mm) densely pubescent leafy peduncle; capsule conical, densely tomentose with 2-3 mm pedicel; flower bract light brown.

Native habitat: Europe. Widely distributed on moorland (Newsholme, 1992).

Hardiness: Zones 4-7.

Growth rate: Fast.

Phenology: Vegetative growth starts late (toward the end of April) and continues until fall; flowers at the beginning of April.

Landscape value: Not particularly ornamental, yet hardy hybrid; male specimen with the same parentage may be considered more attractive.

Notes: Not available in the nursery trade.

Salix apoda Trautv.

Synonyms: *S. hastata* L. var. *apoda* Laksch.

Habit: Dwarf or low shrub with stiff horizontal branches.

Size: 0.1-0.3 m high and wide.

Native habitat: Europe. Caucasus, Elbrus Mts.

Hardiness: Zones 4-7.

Landscape value: One of the most attractive willows for rock gardens.

Notes: Small male species with elliptic leaves and wooly gray precocious flowers with orange-red anthers. Unfortunately have not been able to grow this species; specimens obtained from American nurseries appear to be *S.* x*simulatrix*; according to R.Kaye (1972), difficult to establish from cuttings: rooted cuttings collapse before they can be potted.

Salix arbuscula L.

Habit: Low to medium size, densely branched shrub.

Size: Polymorphic species with a wide range of sizes (from 0.3 to 1.3 m tall); at high elevations more prostrate growth.

Stems: Diameter: 1.5 mm at the tip and 4 mm at the base; upper portions brown, lower green-brown, glabrous and glossy.

Buds: 3 x 2 mm, color as stem; blunt oblong.

Leaves: 25 x 15 mm; elliptic to obovate, glandular serrate; bright green and glossy above, paler to glaucous below; acute or obtuse apex, cuneate base.

Flowers: Coetaneous; male catkins 8 x 5 mm, ovate with 6-7 leaflets; abundant.

Native habitat: Europe. Scandinavia, Scotland, Northern Russia; mostly on basic rocks.

Hardiness: Zones 3-6; under drought stress can lose foliage sooner that the other species, but will refoliate quickly; can be severely affected by black spot.

Growth rate: Fast.

Phenology: Starts growth beginning of April and continues till beginning of June; flowering second or third week of April; by the beginning of June some foliage may be affected by black spot.

Landscape value: Prostrate specimens can be used as groundcover for small rock gardens; it has bright green glossy foliage and is very ornamental during flowering; flowering lasts for a few weeks, much longer than other *Salix* species; can be grafted onto standard; despite its stained foliage problem it is still worth growing.

Notes: Available in the nursery trade only in Europe.

Salix arctica Pall

Common name: Arctic Willow.

Habit: Prostrate thick branched dwarf shrub; very polymorphic species changing its appearance throughout its wide range of natural distribution.

Size: 0.05-0.15 m high and wide.

Stems: Diameter: 1-1.5 mm at the tip, 2-3 mm at the base, brown; pubescent later becoming glabrous; sometimes partially buried in the ground; stems rooting where they touch the ground.

Buds: 3 x 1.5 mm; color as stem.

Leaves: 30-50 x 10-20mm; leathery; obovate or elliptic; apex acute or rounded, base cuneate or rounded; mature leaves glabrous with marginal hair; light-green or yellow-green on the upper surface, glaucous underneath; prominent venation; variable in size and shape; adpressed hairs on the lower leaf surface may persist as a 'beard' at the leaf tip

Flowers: Coetaneous; observed specimens did not bloom.

Native habitat: North America and Eurasia; arctic, alpine and subalpine regions.

Hardiness: Zones 1-6.

Growth rate: Slow (2-2.5 cm per year).

Phenology: The earliest species to foliate in spring (middle of March), to finish annual growth (at the end of May) and to shed the foliage (at the beginning of August); from August till Match it is dormant.

Landscape value: Not particularly ornamental; taller ecotypes can be of interest for small rock gardens as structural elements and as earliest foliage specimens in spring; smaller ecotypes difficult to maintain free from overcrowding; long dormant season makes it less attractive.

Notes: Available in the trade. An interesting fact is that in the wild *S. arctica* can live 100-200 years (Argus, 1999). *Salix arctica* var. *petraea* common in cultivation appear to be *S. glauca*.

Salix* x*ausserdorferi Hut. (*S. glaucosericea* Flod. x *S. retusa* L.).

Habit: Dwarf spreading shrub with thick branches.

Size: 0.06 m high and 0.1-0.2 m wide.

Stems: Diameter: 2 mm at the tip 3 mm at the base; light brown.

Buds: 3 x 2 mm, oval blunt; color as stem.

Leaves: 50 x 20 mm; narrowly elliptic with acute apex and cuneate base; glossy dark green above and gray pubescent beneath.

Flowers: Studied specimen did not bloom.

Hardiness: Zones 3-6.

Growth rate: Slow.

Phenology: Starts vegetative growth late (in the middle of April) and finishes by the beginning of June; hold foliage till October.

Landscape value: Similar to *S. glauca* (*S. glaucosericea*), but have a glossy upper leaf surface; very slow growing; not of particular interest.

Note: Not available in trade. Rare hybrid species; probably known only in UK; to our knowledge Newsholme (1992) is the only published reference describing the species.

Salix* x*balfourii Linton (*S. caprea* L. x *S. lanata* L.).

Habit: Wide spreading upright medium-size shrub with stout branches, intermediate in character between the parents.

Size: 0.50-1.5 m high and 0.3-1.0 m wide.

Stems: Diameter: 3 mm at the tip and 5 mm at the base; gray-yellow; puberulent.

Buds: Flower buds much bigger than leaf; dark brown 12 x 6 mm, conical, at 30^{o} angle to the stem; leaf buds reddish 5 x 3 mm triangle.

Leaves: 50 x 30 mm; elliptic; apex obliquely acuminate, base obtuse; young leaves woolly and gray, becoming dark green glabrous on the upper surface and glaucous pubescent underneath; unfolding foliage is pinkish.

Flowers: Precocious; unusual yellow pubescence of flower bracts, which are typically white for most of *Salix* (another species exhibiting such characteristic is *S. subopposita*); male catkins 30-40 x 12 mm, oblong with 3-4 leaves at the base; bracts green with black tips; anthers yellow.

Native habitat: Originated in Scotland (Newsholme,1992) or in England in 1890 (Krussmann, 1985).

Hardiness: Zones 4-6.

Growth rate: Medium.

Phenology: Loses its scales by the middle of March and exhibits interesting yellow catkins for 4-5 weeks, before it starts flowering (third week of April); vegetative growth continues from the middle of April till beginning of June; holds foliage till late October.

Landscape value: Very attractive for its early catkins of unusual yellow color and gray foliage; interesting architectural element for rock gardens and small urban gardens; can be maintained as dwarf specimen by coppicing.

Notes: Not available in the nursery trade in USA.

Salix* x*boydii Linton. (*S. lanata* x *S. reticulata*)

Habit: Dwarf or low upright shrub, forming a gnarled miniature tree.

Size: 0.1-0.3 m tall.

Stems: Diameter: 1mm at the tip 2 mm at the base; short; olive-green, pubescent when young, later glabrous.

Buds: 1x1 mm; light brown.

Leaves: Small circular, closely set; 10-15 mm diameter; firm texture; gray-green on the upper surface, silvery gray underneath; unfolding leaves pubescent, later woolly only beneath; margin entire, slightly waved; base cordate; prominent veins; petiole very short.

Flowers: Precocious; rarely produced; observed specimen did not flower.

Native habitat: Europe. Scotland.

Hardiness: Zones 4-6, tolerant of light shade (Encyclopedia of Garden Plants, 1992).

Growth rate: This is the slowest-growing willow; annual growth 1-2 cm; at 40 years 30 inches high; at the collection 2 year old plant 0.05 m tall.

Phenology: Start vegetation very late: last week of April and growth continues till 1-2 week of June.

Landscape value: Very nice miniature tree of "ancient" majestic appearance; one of the most interesting species for alpine and trough gardens, but needs to be closely monitored due to its small size.

Notes: A natural hybrid found by Dr.W.Boyd in mountains of Scotland. It is unclear if all currently available plants came from this original clone; according to Krussmann (1985) apparently all the plants in cultivation are males**;** according to Newsholme (1992) it is a female clone. According to some sources (Newsholme, 1992, Griffiths, 1994) is a hybrid of *S. lapponum* x *S. reticulata*. Rare in trade in USA.

Salix brachycarpa Nutt.

Habit: Medium-size shrub with ascending stiff branches.

Size: 0.50-1.50 m.

Stems: Diameter: 2 mm at the tip, 3-4 mm at the base; purple-brown to light brown; new growth pubescent; flaky epidermis on older shoots.

Buds: 3 x 1.5 conical, brown or purple.

Leaves: 50 x 15 mm; ovate; young densely pubescent, sparsely pubescent when mature; light-green above, glaucous beneath; apex acute; base acute or obtuse; entire margin; petiole very short (2-3 mm).

Flowers: Coetaneous; female catkins densely flowered, 10 x 4mm on 3-5 mm leafy peduncle; ovary densely pubescent, sessile with red branched stigma and style; floral bracts tawny or brown, very hairy.

Native habitat: North America: Western USA and Canada.

Hardiness: Zones 4-6.

Growth rate: Fast.

Phenology: Vegetative growth starts early – the middle of March and finishes by the beginning of June; drops foliage early (August) and the remainder of the season only barren stems; flowering in the middle of April.

Landscape value: Year round characteristic element in the medium size garden; can be used in mass; not particularly ornamental flowers located along the stem and usually hidden by unfolding foliage. '**Blue Fox**' is a low growing (up to 0.5 m) cultivar of *S. brachycarpa*. Effectively used in mass in the Toronto Music Garden.

Salix* x*brevipens Flod. (possibly hybrid of *S. breviserrata* x *S. rosmarinifolia*).

Habit: Low shrub with somewhat ascending and spreading branches.

Size: 0.3 m high and wide.

Stems: Diameter: 1.5 mm at the tip 4 mm at the base; light beige-brown, older stems gray; mature stems glabrous.

Buds: Flower 6 x 3 mm, at 45^{o} angle to the stem, broadly conical, orange-brown; leaf 3 x 1.5 mm, conical.

Leaves: 30 x 10 mm, narrowly elliptic, dark green on the upper surface and lighter and pubescent beneath; entire or minutely serrate margin; acute apex, obtuse base.

Flowers: Coetaneous; male catkins 15 x 5 mm on leafy peduncle; flower bracts purple with dark tip; anthers purple, filaments pink.

Hardiness: Zones 4-6.

Growth rate: Medium.

Phenology: Vegetative growth from beginning of April until beginning of June; flowers in the middle of April.

Landscape value: Interesting specimen for small rock garden especially during flowering with its ornamental purple inflorescences; the remainder of the season not very striking.

Note: Not available in the trade in the USA.

Salix candida Fluegge

Common name: Sage willow, Hoary willow.

Habit: Low or medium shrub with erect stems.

Size: 0.5-1.5 m and 0.2-0.8 m wide.

Stems: Diameter: 2 mm at the tip 5 mm at the base; brown or purple-brown; pubescent at first, later glabrous; epidermis flaky, branches villous or woolly.

Buds: 4 x 2 mm; broadly conical; densely pubescent.

Leaves: 5-10 x 10-20 mm; narrowly elliptic; young leaves densely pubescent on both sides, later dull green and somewhat pubescent above and villous beneath; apex and base acute, margin undulate; impressed venation above, prominent midrib beneath, pubescent petiole 5-7 mm long.

Flowers: Coetaneous; catkins just below tip of previous year's shoot; male 10-15 x 5-7; anthers purple becoming yellow; female 25-30 x 7-10 mm; ovary densely pubescent; style 0.5-1 mm.

Native habitat: North America; boreal forests; moist alkaline soils.

Hardiness: Zones 4-6.

Growth rate: Medium or fast, depending on origin; specimens from Newfoundland grew 0.15-0.18 m, while an Ohio native had 0.8 m annual growth.

Phenology: Vegetative growth from beginning of April till June; flower by the beginning of May; in cultivation was pH and moisture adaptable.

Landscape value: Small ecotypes can be used in the rock garden; ornamental by virtue of its cottony leaves and attractive male flowers; overall appearance gray-green throughout the season. Ohio native specimen was not particularly ornamental, while the specimen from Newfoundland had nice small gray foliage and maintained dwarf growth.

Notes: This species (as well as *S. humilis*) commonly misidentified in Europe (a few specimens from European collections appear to be something else). Not available in trade.

Salix caprea L. **'Pendula'**

Common name: Weeping goat willow or Weeping pussy willow.

Synonyms: *S. caprea* 'Kilmarnock'.

Habit: Short-arched small weeping tree when grafted; ground cover on its roots.

Size: Variable, depending on the stock (1.8-3 m); on its own roots 0.15-0.25 m high and 0.5-0.7 m wide.

Stems: Diameter: 6 mm at the tip, 10 mm at the base; stiff, green or green-brown.

Buds: Flower: 6 x 3mm, dark-brown or yellow-green, ovoid, very prominent; leaf 4 x 3 mm light-brown.

Leaves: Large, 50 x 25 mm, broadly elliptic; green at the top and grayish green at the bottom; pubescent; rugose; unfolding foliage reddish; inconsistently yellow in fall.
Flowers: Precocious; 30-40 x 20 mm, flower bracts densely pubescent; yellow anthers; very ornamental.
Hardiness: Zones 4-6.
Phenology: Flowering last week of March- first week of April; a few weeks before actual flowering occurs, flower buds lose the scales and silvery catkins appear on the plant; vegetative growth starts immediately after blooming and continues until September.
Growth rate: Fast.
Landscape value: On its own roots is very effective in raised beds, forming a large mound; grafted form with stiff pendulous branches and prolific catkins can be used as a nice specimen for the small garden; very ornamental all year around near water, in rockery, as a specimen on a lawn; its major asset are catkins in spring.
Notes: *S. caprea* 'Pendula" probably is represented by two clones, male and female, and there is confusion with their nomenclature. Original Kilmarnock Willow was a female weeping clone discovered by Thomas Lang of Kilmarnock, Ayrshire, on the River Ayr, Scotland (before 1853). But later only male plants were cultivated under this name in Europe. These days the female clone is named as *S. caprea* 'Weeping Sally' and probably *S. caprea* 'Pendula' (syn. *S .caprea* 'Kilmarnock') should be used only for the male clone.

Authors saw the female clone which is more vigorous, but not particularly attractive, only in England (Westonbirt Arboretum), and it is probably not in commerce in the USA. Grafted specimens require occasional pruning of side branches (arising from understock) and would benefit from pruning of scion stems to increase the density of the crown. Common in trade in USA.

Another cultivar, *S. caprea* 'Curly Locks', is probably a sport of 'Pendula' and differs by its curly shoots. It supposed to be a very ornamental cultivar popular in European countries. We tried to obtain it from American nurseries, but what we got appears to be *S. babylonica* 'Crispa' instead.

Salix cinerea L.

Common name: Gray willow

Habit: Tall shrub, but by occasional coppicing can be kept as medium-size upright shrub.

Size: 4-6 m tall.

Stems: Diameter: 3 mm at the tip, 6-7 mm at the base; red-brown, pubescent.

Buds: Flower: 7-10 x 5mm, red-brown, ovoid; leaf 4 x 3 mm light-brown.

Leaves: 50-70 x 30-40 mm; elliptic, dull green sparse-pubescent above, gray pubescent underneath; apex acute; base cuneate; margin crenated or serrated.

Flowers: Precocious; male: 20 x 8 mm, flower bracts densely pubescent; anthers yellow.

Native habitat: Europe and west Asia.

Hardiness: Zones 2-6.

Growth rate: Medium.

Phenology: Flowering at the middle of April, vegetative growth from middle of April until September. Keep foliage until late October.

Landscape value: Only cultivar **'Tricolor'** is recommended as ornamental. It is very showy in the spring, but in the Midwest by early summer is fading. Requires pruning back a few times during growing season to increase coloration

Notes: Available in trade in USA. 'Tricolor' (syn.'Variegata') is a cultivar with pink-cream-green speckles on leaves, usually smaller than species. There is some confusion with variegated forms of *S. cinerea*. According to Krussmann (1985) this is a female cultivar (our specimens were male). According to Griffiths (1994) 'Tricolor' is a synonym of 'Variegata'. According to Newsholme 'Variegata' is another cultivar with green and white variegation.

Salix coesia Vill.

Common name: Blue willow.

Synonyms: *S.caesia* Vill.

Habit: Medium upright short-branched straggling shrub.

Size: 1 m tall and wide.

Stems: Diameter: 1mm at the tip 4 mm at the base; glossy brown or purple-brown with a little bloom.

Buds: 3 x 1.5 mm; glabrous; color as stem.

Leaves: 20-25 x 10 mm; leathery, glabrous; mature leaves bluish green above, whitish-gray beneath; obovate or elliptic; apex acuminate, base obtuse; prominent midrib; entire margin; small 1-2 mm petiole.

Flowers: Coetaneous; female cylindrical 10 x 4 mm on 3-5 mm leafy peduncle; ovary pubescent; stigma purple bifid, small style, almost sessile; male the same size; not abundant; stamens purple-red at first, mature yellow.

Native habitat: Eurasia. Central Asia, scarce populations in Alps.

Hardiness: Zones 4-6.

Growth rate: Medium.

Phenology: Begins vegetative growth by the middle of April and finishes by the middle of June; one of the latest species to bloom (end of April).

Landscape value: The major asset is beautiful bluish foliage; can be grafted onto a standard and grown as a small pendulous plant; attractive by virtue of its foliage until late October.

Notes: Many authors listed it as *S. caesia* Vill.; we follow Skvorsov (1968) who considers *S. coesia* Vill. as a correct spelling (based on prevailing rule of taxonomic priority). The specimens of this species arrived also under the name *S. starkeana* (UK) and *S. bakko* (Poland).

Salix crenata Hao

Habit: Dwarf mat-forming shrub with long creeping stems.

Size: 0.15 m high and 0.3 m wide.

Stems: Diameter: 2 mm at the tip and 3 mm at the base; yellow-brown or orange-red; flexible; ribbed.

Buds: 2 x 1.5 mm, small, ovoid, colored as stem.

Leaves: 15 x 8 mm; elliptic; light green above, lighter underneath; apex and base acute, slightly wrinkled, midvein raised underneath; petiole 5 mm long, twisted, red.

Flowers: Coetaneous; 5 x 3 mm; catkins very small with just a few flowers; flower bracts yellow-green; anthers yellow, ovary glabrous.

Native habitat: China: west central and south central mountains regions (4300-4800 m).

Hardiness: Zones 5-7.

Growth rate: Fast.

Phenology: Vegetative growth from the beginning of April until September; flowers in the middle of April (very sparsely).

Landscape value: Interesting specimen fro the rock garden with bright stems and vivid green foliage.

Notes: Available in trade.

Salix* x*doniana Sm. (*S. repens* L. x *S. purpurea* L)

Habit: Medium upright shrub with flexible branches.

Size: 1.5-2 m tall and 0.7-1 m wide.

Stems: Diameter: 2 mm at the tip 5 mm at the base; gray or purple-gray glabrous with a little bloom; very flexible.

Buds: Flower 3 x 1.5 mm purple conical; leaf 2 x 1.5mm triangle.

Leaves: 25-40 x 7-12 mm; at first pubescent, mature glabrous on both sides; bluish-green; apex and base acute; margin entire or serrated; short petiole; some of the leaves are opposite or subopposite (as *S. purpurea*)

Flowers: Precocious; 12 x 5 mm anthers red later yellow.

Hardiness: Zones 4-6.

Growth rate: Fast.

Phenology: Flower at the beginning of April; vegetative growth continues from middle of April till September; retains foliage till November.
Landscape value: Looks very similar to its parent *S. purpurea*; does not possess any outstanding ornamental features.
Note: Not available in trade.

Salix elaeagnos Scop.

Common name: Hoary willow, Rosemary Willow
Habit: Small tree, but by occasional coppicing can be kept as medium size upright shrub.
Size: 8-10 m high and 4-5 m wide.
Stems: Diameter: 2 mm at the tip, 6-7 mm at the base; pubescent at first, later glabrous; dark purple.
Buds: Flower: 6-7 x 3mm conical, purple; leaf: 3 x 1.5 mm triangular.
Leaves: 70-100x 10-30 mm; linear; both sides gray pubescent at first, later glabrous above; apex and base acute; margin serrated revolute; petiole 4-8 mm; turning yellow in fall; some dry leaves stay on plant until spring.
Flowers: Coetaneous 30-40 x 6-8 mm; flower bracts pale; ovary glabrous.
Native habitat: Mountains of North Africa and central and southern Europe; prefers calcareous soils.
Hardiness: Zones 4-7.
Growth rate: Fast.
Phenology: Starts growth and flowering in the beginning of April and growth continues until September. Stays ornamental until late October.
Landscape value: Very graceful shrub with feathery rosemary-like gray foliage (sometimes called 'Monster rosemary plant'). Also attractive in winter with its round bamboo-like wands and compact dense crown. Excellent by the water, nice addition for the perennial border. Tolerant of drought. Often in cultivation under wrong name *S. rosmarinifolia*.

Salix* x*finnmarchica Willd. (*S. myrtilloides* L.x *S. repens* L.).

Synonyms: *S.* x*finmarchica*.

Habit: Low, procumbent, densely branched shrub; its growth habit resembles *Cotoneaster*.

Size: 0.15-0.25 m high and 0.2-0.4 m wide.

Stems: Diameter: 1mm at the tip and 3 mm at the base; glabrous; purple-brown, very thin.

Buds: 2 x 1.5 roundish, pubescent, purple-brown.

Leaves: 15-20 x 5-7 mm; broadly elliptic small; at first pubescent, later glabrous; dark green, lighter underneath, red petiole.

Flowers: Precocious; 8 x 4-5 mm; catkins are small rounded with 2-3 leaflets at base; very abundant; only female clones, pink scales.

Native habitat: Europe. Sweden, Norway.

Hardiness: Zones 4-6.

Growth rate: Fast.

Phenology: Flowers at the beginning of April; vegetative growth from middle of April till beginning of June; retains clean foliage until November.

Landscape value: Ideal for small rock gardens; ornamental till late fall; light leaf spot pressure from the beginning of summer; can be grafted onto a standard.

Note: Not available in trade in the USA.

Salix foetida Schleich.

Habit: Low or medium compact densely branched shrub; upright or procumbent.

Size: 0.3-1.2 m high and wide.

Stems: Diameter: 1.5 x 3mm; brown or purple brown; glabrous.

Buds: Color as stem; 3 x 1.5 mm, conical.

Leaves: 25 x 15 mm elliptic, glabrous; serrated margin with glands at the end of teeth; deep green and glossy above, glaucous beneath.

Flowers: Coetaneous; male catkins 10 x 3 mm on 5-7 mm leafy peduncle; flower bracts light; stamens yellow; very scarce; female catkins 7 x 5 mm on leafy peduncle; gray pubescent; stigma red bifid.

Native habitat: Europe. Subalpine and alpine zones of Alps and Pyrenees; prefers moist acid substrate.

Hardiness: Zones 4-6.

Growth rate: Fast.

Phenology: Foliate in the middle of April; flower at the end of April; growth continues until middle of June; clean foliage till October.

Landscape value: Interesting miniature tree for the rock garden for its crown architecture and in containers (naturally branched to the based can be pruned to form a "bonsai" type"); all year round interest.

Notes: Not available in trade in the USA.

Salix* x*friesiana Anderss. (*S. viminalis* L. x *S. repens* L.).

Habit: Upright, rigid medium-size shrub.

Size: 0.5-2 m tall and wide.

Stems: Diameter: 2mm at the tip and 5-6 mm at the base; purple-brown; new stems puberulent.

Buds: Flower: 8 x 4 mm ovate, dark-purple or purple-brown puberulent; leaf 3 x 2mm triangular.

Leaves: 50-70 x 10-15 mm; dull green above, densely pubescent beneath; apex and base acuminate; margin slightly revolute; short petiole; lanceolate stipules.

Flowers: Precocious; very profuse male catkins, 15-30 x 5-7mm; anthers yellow; dense (10-13 per 0.1 m).

Native habitat: Rare hybrid originally found in Scotland and later reported in other European countries as well.

Hardiness: Zones 4-6.

Growth rate: Fast.

Phenology: By the middle of March is losing bud scales and reveal inflorescences; flower in the middle of April; vegetative growth from middle of April until October.
Landscape value: Prolific bloomer; very attractive in March-April by virtue of its catkins; the remainder of the season not particularly interesting; appropriate for small gardens and for cut flowers in early spring.
Notes: Krussmann (1985) listed *S. friesiana* Anderss. as a synonym for *S. rosmarinifolia*. Not available in trade in the USA.

Salix* x*gillotii Camus (*S. lapponum* L.x *S. phylicifolia* L. or *S. myrsinifolia* x *S. retusa*)
Habit: Dwarf or low wide-spreading or semi-prostrate densely branched shrub.
Size: 0.20-0.25 m high and wide.
Stems: Diameter: 1mm at the tip, 3 mm at the base; olive with purple-brown puberulent tips; older stems gray.
Buds: 2.5 x 1.5 mm, oblong.
Leaves: 30 x 15 mm; elliptical, apex acute, base cuneate or obtuse, margin serrated; at first pubescent, later glabrous; dark green above and glaucous beneath; light yellow fall coloration.
Flowers: Coetaneous; female; 15 x 6 mm on a leafy peduncle; very scarce; flower bracts light green, pubescent.
Native habitat: Europe. France (according to Krussmann (1985)), or mountain regions of Scandinavia (according to Newsholme (1992)).
Hardiness: Zone 4-6.
Growth rate: Medium.
Phenology: Begins vegetative growth and flowering at the beginning of April, finishes by the beginning of June; flower at the end of April; light leaf spot throughout the summer.
Landscape value: Not particularly attractive; only female clone is known. Not available in trade in the USA.

Salix glauca L.

Common name: Arctic gray willow, Gray-leaf willow.

Synonyms: *S. glaucosericea* Flod.

Habit: Low to medium size shrub, rarely prostrate form.

Size: 0.5-1.5 m high and 0.3-1 m wide.

Stems: Diameter: 2 mm at the tip 6 mm at the base; stout, yellow-orange, brown, very tip puberulent, but mostly glabrous and glossy.

Buds: 5 x 3mm, blunt, color as stem.

Leaves: 30-40 x 15-25 mm; elliptic or obovate; thick texture; apex and base acute or obtuse; margin nearly entire, sometimes revolute; first pubescent, mature glossy green above, glaucous green beneath; slightly prominent veins; unfolding foliage reddish; a few dry leaves stay on the plant until spring.

Flowers: Coetaneous; male, very abundant; 20 x 6 mm on leafy peduncle, anthers yellow, flower bracts very light with beige tips; female 30 x 10 mm cylindrical, ovaries densely pubescent.

Native habitat: North America, Eurasia. Circumpolar species; prefers acid substrate; usually forms a big mass of numerous plants.

Hardiness: Zones 2-6. Very hardy.

Growth rate: Fast.

Phenology: Vegetative growth from beginning of April until early June, flowers middle of April; occasional flushes of growth throughout the summer; light leaf spot pressure at the end of summer; holds foliage very late (until December).

Landscape value: Stout and bushy with attractive bright foliage through the season; interesting with stout bare stems in winter time; prolific flowers in spring; excellent for coarse texture and structural effects; some yellow coloration in fall; holds leaves late into a fall.

Notes: Not available in trade. *Salix glauca* is a very polymorphic species; great variation can be found in sizes of plants in native populations. Some geographical and morphological variants of this species have been given species status. Many authors listed *S. glaucosericea* Flod. (Alpine gray willow) as a separate species. We follow Skvortsov (1968) and consider it as a synonym of *S. glauca* and its ecotype naturally growing in Alps with more prominently silky pubescent leaves. The specimen in our Ohio collection was very low and slow growing.

Salix* x*grahamii Borrer. (*S. herbacea* L.x *S. phylicifolia* L., or *S. herbacea* L.x *S. myrsinites* L.or *S. herbacea* L.x *S. aurita* L.x *S. repens* L.)

Habit: Dwarf or low mounded shrub.

Size: 0.15-0.3 m tall and wide.

Stems: Diameter: 1mm at the tip 2mm at the base; green or light brown, slightly puberulent at tip.

Buds: 4 x 3 mm, orange-brown, blunt.

Leaves: 30 x 20 mm elliptic, dark green on upper side, light green beneath; glossy, firm texture; apex obtuse or acute, base rounded; unfolding pubescent, becoming glabrous later; margin wavy; prominent venation underneath.

Flowers: Coetaneous; female; 10-15 x 3-4 mm on leafy peduncle; flower bracts green, ovary flask- shaped; upper portion dark purple, lower green, glabrous; long (2 mm) style; double cleft stigma.

Native habitat: Europe. Scotland.

Hardiness: Zones 4-6.

Growth rate: Fast.

Phenology: Vegetative growth starts at the beginning of April and finishes by June; flower in the middle of April; at the beginning of summer severe leaf spot (up to 70 % of leaves affected) and rust.

Landscape value: Can be used as groundcover in small rock gardens; would be authors last choice because it is affected more severely than other *Salix* species by leaf spot. Can be grafted onto a standard.

Notes: Available in trade. **'Moorei'** (*S.* x*moorei* White) is a prostrate to flat female cultivar with small shiny green leaves and precocious flowers. The nomenclature of this species and the information about its parentage is confusing. According to some authorities (Krussmann, 1985), *S.* x*grahamii* Borrer. and *S.* x*moorei* White are the natural hybrids between *S. herbacea* and *S. phylicifolia*, originally found in Scotland, reaching 30cm height; also adding a note that *S. xmoorei* is female hybrid (but no reference on sex of *S.* x*grahamii*). According to others (Griffiths, 1994) *S.* x*grahamii* Borrer. is a hybrid of *S. herbacea* x *S. aurita* x *S. repens* (female) and 'Moorei' is listed as a cultivar with narrow-oblong scales.

Salix helvetica Vill.

Common name: Swiss willow.

Habit: Low-medium upright rounded shrub with thick branches.

Size: 0.5-2 m high and wide.

Stems: Diameter: 3 x 5 mm, pubescent at first, later glabrous and glossy; yellow, yellow-gray or olive; short internodes.

Buds: Color as stem; 6 x 3 mm yellowish or reddish, blunt, pubescent or glabrous.

Leaves: 4 x 2 mm, obovate or elliptic, apex and base acute, margin entire, young leaves are densely pubescent, later gray and sparsely pubescent above, silvery tomentose beneath.

Flowers: Coetaneous; 15 x 8 mm on leafy peduncle, flower bracts light with brown tips, anthers dark-red becoming yellow when mature.

Native habitat: Europe. Alps, Tatry Mountains; subalpine and alpine zones; prefers acidic soils.

Hardiness: Zones 4-6; very hardy in Ohio.

Growth rate: Fast.

Phenology: Vegetative growth from beginning of April until beginning of June; flower in the middle of April; blooming time may be very short, as our observations in Columbus, Ohio, coincided with unusually hot spring days (90^{o}F).

Landscape value: Superb species for an alpine garden. According to some sources this species is very sensitive to rust, but throughout our observations over several years, foliage has remained very clean. Attractive all year round by virtue of its ornamental foliage, flowers and characteristic skeleton during dormant season. Can be grafted onto a standard.

Notes: Not available in trade.

Salix herbacea L.

Common name: Dwarf willow, Least willow, Snowbed willow.

Habit: Dwarf prostrate shrub with stems branching and creeping below the surface; sometimes only tips of branchlets or foliage rises above the ground.

Size: 10-50 mm high and 50-70 mm wide.

Stems: Diameter 1mm at the tip and 1 mm at the base, slender, olive or brown, glabrous.

Buds: Color as stem, 1.5 x 1 mm, ovoid, blunt.

Leaves: 8 x 15 mm; ovate; deep green and glossy on both sides; apex rounded, base rounded or kidney-shaped; serrated margins overlapped at the base; veins visible on both sides; petiole 3-5 mm.

Flowers: Coetaneous; catkins reduced in size with 10-12 flowers of leafy peduncles; male are minute 5-6 mm long, filaments yellow; female 10-12 mm.

Native habitat: North America (arctic tundra) and Europe (common in all high mountain areas); prefers acidic substrate, but grows on basic soils as well.

Hardiness: Zones 2-6.

Growth rate: Very slow, 20-30 mm a year.

Phenology: Starts vegetative cycle in the middle of April, finishes growth at the end of May; did not bloom.

Landscape value: The smallest *Salix,* without any outstanding ornamental features; can provide a green mat in the rockery or be placed in a container. *S. serpyllifolia* is related to *S. herbacea* and is very similar in appearance, but grows faster, so it can be recommended to achieve the same effect.

Salix hylematica Schneider

Synonyms: *S. fruticulosa* Andersson, *S. furcata* Andersson, *S. nepalensis* Hort.

Habit: Dwarf or low spreading shrub.

Size: 0.15-0.2 m and 0.5-0.6 m wide.

Stems: Diameter 1mm at the tip and 2 mm at the base; red-brown or purple; young growing stems hairy, later glabrous.

Buds: 2 x 1.5 mm purple, glabrous.

Leaves: 5-10 x 3-5 mm; elliptic, glabrous and glossy above, glaucous beneath; serrated toward the apex or entire; petiole 3-5 mm.

Flowers: Coetaneous; catkins 5-10 mm long on short lateral leafy branches with peduncle; flower bracts red-purple; style deeply 2-lobed; fruiting catkins red; 2 linear nectaries at the base of flower.

Native habitat: Asia; alpine zone (3000-4000m) of West Himalayas; Uttar Pradesh to Bhutan; common in Nepal.

Hardiness: Zones 6-8. In Zone 5 flower buds can be injured, but vegetative organs survive.

Growth rate: Medium.

Phenology: Same as *S. lindleana*.

Landscape value: Very unusual low spreading shrub with ornamental leaves and attractive catkins for use on exposed sits of rock gardens.

Notes: Species very similar to *S. linleyana*, but differs by more spreading, laxer growth, hairy young shoots, catkin axis and stamen filaments, as well as somewhat larger catkins (Polunin, 1984).

Salix integra Thunb.

Synonyms: *S. multinervis* Franch.

Size: 1-4 m high and 1-2 m wide.

Stems: Diameter 1mm at the tip and 5mm at the base; glossy purple-gray, flexible.

Buds: 2 x 1.5 mm roundish glabrous, red-brown, subopposite.

Leaves: 30-50 x 7-15 mm; bright green or yellow-green above, glaucous beneath; oblong; apex obtuse, base rounded or cordate; margin mostly entire; nearly sessile, opposite juvenile leaves pink colored; slight yellow coloration in fall; keeps some old foliage until spring.

Flowers: Precocious or coetaneous; 15 x 3 mm cylindrical; on leafy peduncle; not ornamental.

Growth rate: Fast.

Phenology: Flowers at the end of March or beginning of April, vegetative growth continues from the beginning of April until middle of September; keep green foliage late into the season (until December).

Native habitat: Asia (Far East of Russia, China, Korea, Japan).

Hardiness: Zones 4-6. During cold winters, the shoot tips may be injured.

Notes: The following cultivars are superior to the species.

'Pendula'

Very ornamental low or medium shrub (0.6-1 m high and wide) with long pendulous branches. Dense structure of arching red shoots, attractive during dormant season; can be grafted on a standard. Very effective when planted over a big rock, retaining wall or in a large planter 0.5-1 m above the ground. Female cultivar of Japanese origin. Available in trade only in Europe.

'Hakuro-Nishiki'

Common name: Dappled willow

Synonyms: *S. integra* 'Itakuro-Nishiki' (Griffith, 1994), *S. integra albomaculata*, S. 'Fuiri-koriyanagi').

Cultivar with white and pink variegated foliage: first 2-3 pairs of leaves green then 2-3 white variegated, then pink-variegated. At the beginning of June, pink variegation disappears and the rest of the season is mostly white or only green. It is recommended to prune a few times throughout the season to enhance the coloration (last pruning should be done by August). In Midwest it is ornamental only until beginning of summer, later fading in the sun. In the humid climate of the Northwest, the variegation is much brighter and remains longer throughout the season, and there this cultivar will reach its full ornamental potential. Forms a mounded shrub on its own roots. Often sold as graft on a standard. During recent years has became popular in USA trade.

Salix lanata L.

Common name: Woolly willow.

Synonyms: *S. depressa* L., *S. glandulifera* Flod.

Habit: Low or medium erect shrub with stiff divaricated branches.

Size: 0.5-1 m high and wide (occasionally reaching 2-2.5 m in wild); creeping in severe conditions.

Stems: Diameter 3 mm at the tip, 5 mm at the base; thick; orange-yellow, pubescent when young.

Buds: 5 x 3 mm; darker than stem; roundish; stout at maturity.

Leaves: 50 x 40 mm; roundish or widely elliptical; leathery; dull green above, glaucous beneath; densely-pubescent when young; later tomentose mostly beneath; apex acute; base subcordate; margin entire, somewhat undulate; petiole 50-10 mm; large stipules; reticulate venation; unfolding foliage pinkish.

Flowers: Coetaneous; unusual yellow pubescence of flower bracts: male 40-60 mm long, with yellow anthers; female up to 80 mm long. Our specimen did not bloom.

Native habitat: Eurasia: arctic tundra and northern mountains; on moist but well-drained substrate; prefers basic soils.

Hardiness: Zones 2-6.

Growth rate: Medium.

Phenology: One of the latest to start vegetative growth in spring (during the middle of April) and finishes by the beginning of June. Holds foliage until October.

Landscape value: Attractive year round: in wintertime with stiff branches and bright spherical buds; in summer with its gray woolly foliage. In Europe it is considered the best willow for honey production. Can be grafted onto a standard.
Notes: Available in trade only in Europe. Our specimen was received as *S. lanata*, but may represent the cultivar 'Stuartii' which is smaller than the species, and has gnarled branches, yellow twigs, orange buds in winter, and smaller leaves and larger flowers. The North American species closely related to *S. lanata* is *S. richardsonii* Hook.; it has smaller leaves and less dense pubescence.

'Mark Postill' (*S. hastata* 'Wehrhahnii x *S. lanata*) is a female cultivar of *S. lanata* with less densely pubescent crowded leaves, shorter internodes and prominent broadly cordate stipules; precocious white erect catkins. Raised by propagator Alan Postill from Hillier Gardens (UK) in 1967 and named after his son. A very ornamental cultivar we observed from Hillier Gardens in spring 2000 was 1.5 m high and 1 m wide with prolific flowers. We had a specimen of this cultivar for two years, which grew very slowly (3 year old plant was 70 mm tall), did not bloom and apparently suffers from extreme heat.

Salix lapponum L.

Common name: Downy willow, Lapland willow.
Synonyms: *S. daphneola* Tausch.
Habit: Low or medium densely branched upright shrub.
Size: 0.5-1.5 m spreading to 0.3-1 m.
Stems: Diameter: 1mm at the tip and 5 mm at the base; thin; olive or red-brown; pubescent at tip.
Buds: Flower 3-5 x 1.5 mm, dark-brown or purple, conical, with attenuated tip. Leaf: 2 x 1.5 mm, triangular.
Leaves: 40-60 x 15-20 mm; ovate or elliptic; downy dull green above, densely white-tomentose beneath; apex acute, base cuneate or rounded; entire margin; petiole 7-10 mm

long; one of the latest to foliate (at the same time as *S. lanata* and *S. pyrenaica*); petioles around the generative buds are often inflated.

Flowers: Precocious; male 20-25 mm long, anthers red becoming yellow; female 30-40 mm long with densely pubescent ovaries.

Native habitat: Eurasia: from Scandinavia throughout northwest Russia to Altai and in subalpine zone of some central and south-eastern European mountains (but not found in the Alps).

Hardiness: Zones 3- 6.

Growth rate: Medium-fast.

Phenology: Vegetative growth starts during the middle of April and finishes in June; at the end of summer leaves turn brown; holds its foliage until October. Will benefit from coppicing.

Landscape value: Very suitable for rock garden due to its "alpine look" (silvery foliage, compact habit); suitable for any small garden.

Notes: Available in trade. *S. lapponum* is closely related to *S. helvetica* (sometimes confused in trade), but differ by its inflated petiole surrounding generative buds (especially obvious at the end of season) and buds with acute apex (blunt for *S. helvetica*). **'Grayii'** is a female cultivar of *S. lapponum* with dwarf (only 0.2-0.25 m high) densely branched habit. Densely crowded blue-green leaves are much smaller than species. Buds and stems are dark brown-red, brighter color than *S. lapponum*. Very attractive and hardy small shrub, suitable for rock gardens. The only reference for this cultivar was found in Newsholme (1992).

Salix lindleyana Wallich.

Habit: Dwarf creeping mat-forming shrub.

Size: 20-40mm high spreading to 0.3-0.5 m.

Stems: Diameter: 1 mm at the tip 1.5 mm at the base; very thin and flexible; creeping stems easily layering.

Buds: 3-5 x 2 mm, purple.

Leaves: 10 x 2.5 mm; elliptic-lanceolate almost linear, glossy, hairless; light green above, paler underneath; ovate or acute apex, cuneate base; faint teeth near the apex; petiole 3-5 mm purple; hold some foliage through winter.

Flowers: Coetaneous; female: 10 x 4 mm on 15 mm leafy peduncle; purple flower bract completely cover the green ovary so that overall appearance of catkin is dark purple; bifid stigma.

Native habitat: Asia: alpine zone (3600-4500 m) of Himalayas; Pakistan to Southwest China.

Hardiness: Zones 6-8. In zone 5 does not flower profusely, but the vegetative structures survive.

Growth rate: Fast.

Phenology: Starts vegetative growth at the end of March and continues until September. Flowers in the middle of April**.** The tips of branches (upper 50-70 mm) die in winter, but this should not be considered as the consequence of cold damage, but rather a natural type of growth, typical in its native areas. In fall all nutrients deposit only in lower portions of shoots, where well-developed buds will form. The upper portions of the stems serve only for assimilation throughout the vegetative season (Skvortsov, 1968).

Landscape value: Very interesting supplement for the rock garden where it forms a creeping mat of red stems and unusual glossy foliage turning coppery-yellow in autumn. Interesting in spring with its bright red upright catkins. Plants form colonies by rooting the shoots. Hardly can be considered aggressive, but sometimes requires constraint.

Notes: Available in trade. Similar to *S. hylematica*, but smaller and entirely prostrate; all parts glabrous (more details under *S. hylematica*).This species has been received from some nurseries under the incorrect name *S. myrtilloides* 'Pink Tassel'.

Salix myrsinites L.

Common name: Myrtle willow, Whortle-leaved willow.

Habit: Low spreading or ascending shrub, sometimes forming carpet.

Size: 0.15-0.4 m high and wide.

Stems: Diameter: 1mm at the tip 1.5 mm at the base; red-brown, pubescent when young, later glabrous.

Buds: 1.5 x 1 mm light brown.

Leaves: 10 x 6 mm; round, ovate or obovate; glabrous, succulent; glossy dark green above, paler green underneath with reticulate venation; apex acute or obtuse, base cuneate or rounded; margin glandular-toothed; petiole thick and short; dead leaves persist after withering.

Flowers: dense catkins on leafy peduncles; 40-50 mm long; flower bracts purple; anthers and style purple; erect.

Native habitat: Europe: northern mountains and tundra; in wild prefers basic substrate.

Hardiness: Zones 3-6.

Notes: Not available in trade.

Salix nakamurana Koidz.

Synonyms: *S. yezoalpina* Koidz.

Habit: Low prostrate shrub with thick stems adpressed to the ground or decumbent.

Size: 0.2-0.3 m tall and 0.3-0.5 m wide.

Stems: Diameter: 4 mm at the tip and 5 mm at the base; glabrous; dark yellow or brown.

Buds: 8 x 6 mm; orange-brown, glabrous, blunt.

Leaves: 50x40-50 mm; widely elliptic or rounded; leathery; dark green above, paler green underneath; glabrous; apex rounded; base obtuse or cordate; margin entire, or subentire with a few scattered glands; prominent reticulate venation; petiole 30 mm long; juvenile foliage has very long hair and reddish tint, disappearing after leaf is reaching full size; yellow fall coloration.

Flowers: Coetaneous; male: 35-50 x 10mm on 10-15 mm leafy peduncles, flower bracts 1.5 x 1 mm with long (3-4 mm) hairs on internal side.

Native habitat: Japan: alpine slopes of Hokkaido.

Hardiness: Zones 4-6.

Growth rate: Medium.

Phenology: Begins vegetative growth and flowering during the middle of April and growth continues until middle of June. In September leaves change color to bright yellow and hold until late October. Occasionally keeps old foliage until spring.

Landscape value: Very ornamental in spring with its hairy catkins and juvenile leaves. Excellent addition for the rock garden and very effective in troughs. Can be grafted onto a standard. Has nice golden-yellow fall coloration, but not consistent. In humid climates, serves as a nice widely spread groundcover specimen (as we saw at the University of British Columbia Botanical Garden). May be severely damaged by rabbits or other animals in winter time, so would require some protection.

Notes: This species came into trade as *S. nakamurana* var. *yezoalpina*. According to theFlora of Japan (1965) *S. nakamurana* Koids is species inhabiting alpine slopes of Honshu while *S. yezoalpina* Koidz. inhabiting alpine slopes of Hokkaido. These species are very similar in appearance, but *S. yezoalpina* has more rounded leaves and flower bracts rounded at the apex. We follow Skvortsov (1968) who consider S. *yezoalpina* as a synonym of *S. nakamurana*. Prof. H.Ohashi (Tohoku University, Japan) identified our specimen as *S. nakamurana* Koids subsp.*nakamurana.*

Salix nivalis Hooker

Common name: Snow willow

Very attractive species similar to *S. reticulata*, but smaller (up to 15 mm) from western North America. We saw it growing in the barren rocks on upper slopes of the Rocky Mountains in Colorado.

S. pedicellaris Pursh

Common name: Bog willow.

Habit: Medium upright shrub with slender erect shoots. Can form colonies by layering.

Size: Up to 1 m high and 0.3 m wide.

Stems: Diameter: 2 mm at the tip, 3 mm at the base; glabrous; brown; in the wild stems are decumbent in moss.

Buds: 3 x 2 mm; red or yellow; blunt.

Leaves: 50-70 x 10-15 mm; narrowly elliptic; glaucous and glabrous on both sides; apex acute or obtuse; base acute or entire margin; petiole 2-4 mm long; juvenile leaves reddish.

Flowers: Coetaneous. Catkins on leafy peduncles; male 20 x 6-7 mm cylindrical, anthers yellow (or red becoming yellow); female 25 x 7-10 mm, ovary reddish, glabrous; slender 2-3 mm pedicel exceeding the flower bract; very short style; floral bracts light rose.

Native habitat: North America; northern parts, in sphagnum bogs.

Hardiness: Zones 3-5.

Growth rate: Fast.

Phenology: Begins vegetative growth during the middle of April; flowering two weeks later; growth continues until June.

Landscape value: Species similar to its Eurasian counterpart *S. myrtilloides*. In spite of growing in sphagnum bogs in the wild, grows successfully in well-drained conditions of the garden.

Notes: Not available in trade.

Salix phylicifolia L.

Common name: Tea-leaved willow.

Synonyms: *S. bicolor* Ehrh.

Habit: Medium size upright densely branched shrub.

Size: 1-2 m high and 0.5-1 m wide.

Stems: 1.5mm at the tip and 5 mm at the base; reddish-brown or chestnut color; glabrous and glossy.

Leaves: 25-40 x 10-15 mm; ovate; thick texture; bright green and shining above, whitish or bluish-green beneath; glabrous; acute apex; cuneate or round base; margin entire, serrate or crenate; petiole 8-10 mm long; subcordate stipules; juvenile foliage reddish.

Flowers: Coetaneous; male 20 x 7mm on 5 mm leafy peduncle, anthers yellow, flower bracts gray or black; female up to 60 mm long in fruit, ovary pubescent.

Native habitat: North Europe, northeast Asia; mountains of central and south Europe; adaptable, grows on basic or acid, wet or dry soils.

Hardiness: Zones 3-6.

Growth rate: Fast.

Phenology: Begins flowering and vegetative growth during the beginning of April; finish during the beginning of June; leaf drop at the end of October.

Landscape value: An attractive plant with polished twigs and vivid green foliage. Small clones of *S. phylicifolia* with a broad triangular shape of crown been have recommended for ornamental use by the Botanical Garden of the Urals (Russia), where a search for new cultivars of willow is conducted through the selection from natural populations and hybridization work. **'Strandir'** is a dwarf cultivar (0.15 m tall) we received from Hilliers Garden (UK), allegedly originating in Iceland and possibly representing the low growing ecotype of *S. phylicifolia* from northern part of its distribution. No information about this cultivar has been found in the literature.

Salix polaris Whlnb.

Common name: Polar willow

Notes: Circumpolar species similar to *S. herbacea* but with smaller leaves and entire margins. The specimens received from American nurseries appear to be *S. repens*.

Salix purpurea L.

Common name: Purple willow, Basket willow, Purple osier willow.

Habit: Medium size upright shrub with flexible branches.

Size: 1-1.2 m high and wide.

Stems: Diameter: 2 mm at the top 4 mm at the base; glabrous; all cultivars have very slender gray stems often with purple hue of young shoots; rarely damaged by rabbits and other animals because of very bitter taste of its bark; inside layer of the bark is yellow.
Buds: 2 x 1.5 mm reddish or gray.
Leaves: 30-70 x 5-10 mm, lanceolate or narrowly obovate, blue-green or dull-gren above, paler and glaucous underneath; opposite or subopposite; apex acute; base cuneate; margin serrulate toward the apex or entire.
Flowers: Precocious or coetaneous; 20-30 x 5-7 mm on short leafy peduncle; cylindrical, curved; anthers red, filaments totally connate, so that appear only as a single stamen; ovary pubescent; style very short. Not ornamental.
Phenology: Vegetative growth begins during the end of March and continues until September. Flowering at the beginning of April. Holds clean foliage until late November.
Native habitat: Central and South Europe and mountains of North Africa. Widely cultivated in Europe.
Hardiness: Zones 4-7.
Landscape value: One of the most tolerant species: survives on extremely dry and compacted soil and tolerates some exposure to salt. Old overgrown plants need to be renewed by pruning hard to 6" from the ground in late winter.

'Nana'
Common name: Dwarf purple willow
Synonyms: *S. purpurea* var.*nana* Dieck., *S. purpurea* 'Gracilis' Hort., *S. purpurea* var. *uralensis* Spath.
Medium upright compact shrub with numerous slender branches 1-1.2 m high and 0.8-1 m wide. Leaves 50 x 5-7 mm. Very graceful female cultivar with a finely textured appearance year round. Long-lasting (April to November) delicate bluish foliage during the growing season and attractive densely branched slender stems in winter. Can be used for low hedge. One of the most popular willows in production. Often appears in trade under the common name "Arctic willow"; however, this name should be reserved for *S. arctica* (*S. purpurea* is not the species of arctic origin).

‘Pendula’

Common name: Weeping purple willow.

Synonyms: *S. americana pendula* Hort.

Elegant arching female cultivar with fine structure for small gardens, serving as a miniature weeping tree. Fast growing. Nice in combination with other plant material and near water in the garden. Can be grafted onto a standard, or left unpruned. Called “American weeping tree” or “the poor man’s weeper.” Available in trade.

‘Richartii’

Clone with blue mature leaves and dark brown long branches. Juvenile foliage tinted pink. Similar to ‘Nana.” Fast growing. We observed male and female clones with this name in European gardens (According to Newsholme (1992) supposed to be all male). Effective in the winter garden with its densely and finely branched crown. Popular in Europe.

Salix pyrenaica Gouan.

Common name: Pyrenean Willow

Habit: Low shrub with slender dense branches, attaining spherical form.

Size: 0.2-0.5 m high and wide.

Stems: Diameter: 2 mm at the tip 4 mm at the base, purple-brown, glabrous.

Buds: Slightly lighter than stem; flower 5 x 2 mm, conical; leaf 1.5 x 1 mm, triangular.

Leaves: 2 x 1.3 cm; mature leaves glabrous, except margin; elliptic; base rounded, dark green and shining above, glaucous beneath, margin entire; prominent reticulate venation.

Flowers: Female: 10 x 3 mm; loosely flowered on long (8-10 mm) leafy peduncle; flower bracts tan-brown; capsule roundish, woolly, stigma bifid. Inconspicuous catkins persist on the plant for few months.

Native habitat: Europe. Endemic to subalpine and alpine regions of the Pyrenees.

Hardiness: Zones 4-6.

Growth rate: Medium.

Phenology: Vegetative growth begins during the end of April and ends in the middle of June. Scarce flowers appear during the middle of May and catkins with closed capsules remain on the plant until fall. Very light inconsistent yellow fall coloration. Later in the season occasional black spot on the leaves.

Landscape value: A humble little shrub, suitable for small rock gardens; attractive for its dark green foliage; during the dormant season slender branches unnoticeable; ornamental from May until October.

Notes: Species is quite common in the area of its natural distribution, but in cultivation there are only female clones. Not available in nursery trade in USA.

Salix reinii Fr.& Sav.

Habit: Low or medium upright or low spreading shrub with stiff branches.

Size: 0.25-1.5 m high and wide.

Stems: Diameter: 3-4 at the top 6-7 mm at the base, thick; yellow-orange or brown, glabrous.

Buds: Flower: 8 x 4 mm, brown, conical, leaf 3 x 2 mm triangle, color as stem.

Leaves: 30-60 x 15-30 mm broad and rounded; deep green and glossy above glaucous underneath; apex abruptly acute, base rounded or obtuse, petiole 5-10 mm long; margin serrated.

Flowers: Female: 20 x 7 mm cylindrical; flower bracts green, slender style and bifid stigma; male 25 x 5 mm on leafy peduncle; anthers orange-pink turning yellow; scale green with small beige-brown tip.

Native habitat: Asia; Kuril Islands, Japan (Hokkaido, Honshu); from lowlands to subalpine zones.

Hardiness: Zones 4-6. Flowers (leaflets of peduncle) can be damaged by late frost and become black, but it does not seem to hurt the plant.

Growth rate: Fast.

Phenology: Flowers during the end of March. Vegetative growth from April until June. Shedding leaves in October. Some specimens have a nice golden fall color.

Landscape value: Ornamental mainly by its shiny dark-green foliage; can be used in small gardens for structural effects.

Notes: Not available in trade.

Salix repens L.

Common name: Creeping willow.

Habit: Low or medium prostrate or ascending small shrub with slender twigs.

Size: 0.3-1 m high and wide.

Stems: Diameter: 1.5-2mm at the tip and 4-5 mm at the base; red-brown; flexible; pubescent at first, later glabrous.

Buds: Flower: 3-4 x 2-3 mm purple-red, puberulent, conical; leaf: 2 x 1.5 mm triangular.

Leaves: 20-40 x 10-15 mm elliptic; apex acute and often twisted; margin entire revolute; densely pubescent at both sides, later glabrous above (for some mature foliage pubescent at both sides); short 2-3 mm petiole; venation indistinct.

Flowers: Precocious or coetaneous; female 10-20 x 4 mm on leafy peduncle; gray- silver; ovary pubescent, stigma with pedicel, conical reddish; style very short; male 10 x 4 mm; anthers yellow; flower bracts red-brown.

Native habitat: Europe: western lowlands and mountains, common on sand dunes.

Hardiness: Zones 4-6.

Phenology: Flower during the beginning of April; vegetative growth continues from middle of April until September; holds ornamental foliage until late October.

Landscape value: Very polymorphic species ranging in habit from prostrate to upright shrubs. Widely cultivated for centuries; many cultivars differing in leaf size, pubescence and growth habits have been selected. Flowers are very prolific. Males are especially attractive. All cultivars of *S. repens* can be grafted onto a standard.

Notes: *S. repens* was distributed from American nurseries and arboreta as *S. humilis*.

'Nitida' (syn. *S. repens nitida* Wender, *S. argentea* Sm., *S. repens* var. *argentea*, *S. repens* var. *sericea* Gaud. and often named in trade as *S. arenaria* L.).

Common name: Silver creeping willow.

Common cultivated ecotype of *S. repens* typical for costal dunes areas with silvery foliage on both sides. Very attractive cultivar suitable for small gardens. Excellent addition to the perennial border due to its delicate structure and silvery foliage, effectively combining with perennials. Available in trade.

'Bergen'

Female form with long flexible spreading branches, small-elongated dark green leaves. Our specimens were 0.3 m high and 0.5 m wide and had red-pink stigmas.

'Boyd's Pendulous'

Male clone with long trailing mat forming stems; leaves ovate or oval, pubescent underneath. Very effective in the rock garden. Prolific bloomer. Our specimens were 0.2 m high and 0.4 m wide.

'Iona'

Male clone with more compact habit then 'Boyd's Pendulous'. Our specimens were 0.15 m high and 0.3 m wide.

'Voorthuizen'

Female form of Dutch origin with flexible slender stems, dark green small leaves and small catkins. Our specimen had yellow stigmas with shorter branches than 'Bergen'.

Note: Cultivars 'Boyd's Pendulous' and 'Iona'are available in USA trade and are more attractive than 'Bergen' and 'Voorthuizen'(both of which are female).

Salix reticulata L.

Common name: Net-leaved willow, Netted willow, Net-vein willow, Reticulate willow.

Habit: Dwarf creeping shrub.

Size: 0.1-0.15 m tall and 0.2-04 m wide.

Stems: Diameter: 2 mm at the tip 2 mm at the base; glabrous; short, with just a few leaves per stem; can form colonies by layering.

Buds: 6 x 3 mm, light brown, lustrous, blunt.

Leaves: 20-40 x 10-20 mm; broad-elliptic or orbicular; dark green above glaucous gray beneath; leathery; apex rounded, sometimes with a notch; base cordate, margin entire; rugulose (wrinkled) above, reticulate underneath; secondary veins arising almost at a single point at the base; red petiole 10-20 mm long; juvenile leaves with long multidirectional hair; mature leaves become polished dark green.

Flowers: Coetaneous or serotinous; catkins upright; female 30 x 10 mm; ovary pubescent; on long peduncle; male 20 x 7 mm anthers purple later yellow.

Native habit: Circumpolar distribution across North America and Eurasia; alpine and subalpine zones of central and southern European mountains; often on calcareous substrate.

Hardiness: Zones 1-4.

Growth rate: Slow.

Phenology: Vegetative growth from middle of April until June. Under stress may drop its foliage as early as July. Did not bloom. Hardiness in zone 5 needs to be verified. It struggled in our trial in Ohio.

Landscape value: One of the smallest contour-hugging willows (slightly larger than *S. herbacea*) for the rock garden or for trough. Requires open exposure, moist but well drained gravel substrate. Very attractive species but needs close attention to avoid crowding by weeds.

Notes: Available in trade in USA.

Salix retusa L.

Common name: Retuse-leaved Willow, Blunt-leaved willow.

Habit: Dwarf prostrate creeping dwarf shrub.

Size: 0.1-0.15 m high and wide.

Stems: Diameter: 1mm at the tip and 1.5 mm at the base; light-brown, glabrous, rooting.

Buds: 1.5 x 1mm; color as stem.

Leaves: 10-30 x 5-8 mm ovate or obovate, clustered toward the tips; green on both sides; glabrous; blunt with a notch (retuse) tip; base cuneate or rounded; margin entire or with few small teath; veins visible on upper portion of leaves, red petiole 20-40 mm long.

Flowers: 10-20 x 5-10 mm on leafy peduncles; ovary with short style and stigma; anthers and flower bracts yellow.

Native habitat: Europe; alpine and subalpine zones of central and southern mountains; prefer basic substrate.

Hardiness: Zones 2-5.

Growth rate: Slow.

Phenology: Vegetative growth continues from April until June. Did not flower.

Landscape value: Can be used as groundcover with shiny foliage in the rock garden.

Salix rosmarinifolia L.

Synonyms: *S. repens* spp. *angustifolia* Neumann, *S. repens* var. *rosmarinifolia* Koch., *S. angustifolia* Wulfen.

Habit: Medium erect or somewhat prostrate densely branching shrub with thin shoots.

Size: 0.3-2.5 m high and wide.

Stems: Diameter: 1.5 mm at the tip 3 mm at the base; very flexible, pubescent; reddish.

Leaves: 20-50 x 4-10 mm; long linear; dark green above, gray pubescent underneath; erected upward; apex acute (not recurved as *S. repens*); base rounded; entire, slightly revolute margin; prominent midrib with 8-12 pair of lateral veins (*S. repens* only 6-8).

Flowers: Coetaneous; globose or cylindrical catkins on 10 x 6-8 mm on leafy peduncle; flower bracts pubescent; ovary silvery pubescent on 2-3 mm pedicel, style short, stigma and nectary red.

Native habitat: Eurasia; replacing *S. repens* in eastern regions; in stagnant or sandy soils.

Hardiness: Zones 4-6.

Growth rate: Fast.

Phenology: Flowering during the end of March (flowers not prolific). Holds foliage until October. Vegetative growth from the beginning of April until late June.

Landscape value: Species with fine texture of branches, closely related to *S.repens* and morphologically similar to it. Often confused with *S. elaeagnos*, which has the common name Rosemary-leaf willow. Requires hard pruning to keep small size.

Salix saxatilis Turcz.

Synonyms: *S. fumosa* Turcz.

Notes: Saxatilis (latin) means dwelling or found among rocks. It is suppose to be a very ornamental low growing (0.4-0.5 m) species due to its purple catkins. From the Far East of Russia. We received specimens from the Moscow Botanical Garden (Russia) in 1999, but the specimens did not survive. Still, it should be hardy in zones 3-6.

Salix serpyllifolia Scop.

Common name: Thyme-leaved willow.

Synonyms: *S. retusa* var. *serpyllifolia* Wahlenb.

Habit: Tiny prostrate shrub with short stems pressed to the ground and spreading by layering.

Size: 20-30 mm high and 0.2 m wide.

Stems: Diameter: 1 mm at the tip 2 mm at the base; glabrous; light brown, gnarled.

Buds: 2 x 1.5 mm; conical; purple-brown.

Leaves: 4-8 x 4-6 mm; obovate or spathulate; light green on both sides; look succulent; glabrous, shining; apex obtuse or acute; base cuneate; margin entire; withered foliage remains on the plant until the following season, and when the new growth starts to develop and pushes it away.

Flowers: Coetaneous; catkins 5 x 2.5-3 on leafy peduncle, oblong, consist only of 8-10 flowers; flower bract green, glabrous cover almost entirely the ovary; ovary glabrous, pedicel shorter than nectary gland.

Native habitat: Europe: alpine and subalpine regions of mountains of southeast Europe, including Alps. On somewhat dryer soils than *S. retusa*, but not on acid substrate.

Hardiness: Zones 2-5.

Growth rate: Fast.

Phenology: Among the earliest species to foliate; growth continues from the middle of March until June; foliage remains green until October.

Landscape value: Very similar to *S. retusa*, but in all parts much smaller. Flowers not showy. Tolerates some shade. Quickly develops a dense groundcover for the rock garden.

Salix subopposita Miq.

Synonyms: *S. repens* var. *subopposita* Seemen, *S. sibirica* var. *subopposita* Schn.

Habit: Low compact upright shrub with thin shoots.

Size: 0.3 m high and wide.

Stems: Diameter: 1mm at the tip, 3 mm at the base; yellow-green; pubescent.

Buds: 3.5 x 2 mm yellow-brown, round; leaf 1.5 x 1 mm, brown, conical.

Leaves: 20-40 x 7-10 mm; ovate or broadly lanceolate; slightly pubescent light-green above, pubescent gray-glaucous underneath; apex acute; base acute or rounded; margin entire; petiole 5 mm long; prominent venation underneath; opposite or subopposite leaf arrangement.

Flowers: Precocious; male catkin silky, 6-10 x 4 mm; flower bracts red with black tip and yellow hair; anthers golden-yellow; female: 10-20 x 8-10 mm, short-cylindric; ovary pubescent; densely crowded at the upper portion of branches.

Native habitat: Asia: south Japan (Honshu, Kyushu), south Korea.

Hardiness: Zones 5-7.

Growth rate: Fast.

Phenology: Flowering during the end of March, vegetative growth from the middle of April until September. Holds nice green foliage until late October.

Landscape value: Very ornamental year round species by its nest form, hebe-like densely-leaved stems, prolific flowers; decorative for a few weeks; excellent addition for the rock garden. Can be grafted onto a standard.

Notes: Not available in trade in USA.

Salix tarraconensis Pau

Habit: Low species with divaricated shoots.

Size: 0.3 m high wide and spread.

Stems: Diameter: 1-1.5 x 4 mm; purple-brown, puberulent at the tip.

Buds: Flower: 5 x 3 mm broadly conical, black; leaf: 2 x 1mm, triangle, color as stem.

Leaves: 20 x 15mm, almost circular; dark green glabrous above; glaucous underneath; apex and base rounded; margin entire.

Flowers: Coetaneous; male: 10 x 6-7 mm, round, flower bracts purple-pink, anthers purple, later yellow; not very abundant; female: ovary pubescent on 2 mm pedicel.

Native habitat: Europe; endemic species of mountains of northeast Spain (Cataluna); northern slopes, calcareous soils.

Hardiness: Zones 4-7.

Growth rate: Fast; may develop ascending branches when grown in shade.

Phenology: Flower during the middle of April; vegetative growth from end of April until June; holds foliage until late October.

Landscape value: Rare species suitable for rock garden. Can be grafted onto a standard.

Notes: Not available in trade in USA.

Salix variegata Franchet

Synonyms: *S. bockii* Seemen, *S. densifoliata* Seemen.

Habit: Low or medium upright widely spreading, with numerous side short branches.

Size: 1-3 m high in wild; in cultivation 0.5-0.7 m high and tall.

Stems: Diameter: 2.5 mm at the tip 5 mm at the base; pinkish on the upper side, olive-green on the lower; densely pubescent.

Buds: Color as stem; 2 x 1mm, pubescent, triangle.

Leaves: 10 x 4 mm; oblong with tiny petiole; margin almost entire; dark green on the top surface and silvery underneath; holds some of old foliage until spring.

Flowers: Serotinous, on the current year's shoots; female 30-40 x 10 mm on peduncle; flower bracts gray; ovary sessile, pubescent; dry inflorescences stays on the plant till spring.

Native habitat: Asia: north and central China, in high attitudes (up to 2750 m).

Hardiness: Zones 6-8; during cold winters (-15^{o}C) side branches can die above snow line, but plant will grow back from the lower stems; grafted specimens can be covered during the winter; in the winter of 2000-2001 overwintered in Ohio without any damage.

Growth rate: Fast.

Phenology: Vegetative growth start by end of March (one of the earliest species) and continues until September; at the end of August begins flowering which lasts until end of October; green healthy foliage remains on the tree until late October; will require the pruning of old wood in early spring.

Landscape value: The most remarkable species in the garden for fall effect when it is crowded with conspicuous catkins; it is outstanding for its myrtle or *Hebe*-like leave appearance; can be used as a grafted specimen on a 24-40 " tall standard.

Notes: Only the female form has been introduced into cultivation, by Ernest Wilson in 1908. Male plants arealso very attractive (Newsholme, 1992). Some side branches can be damaged in winter, but every year it blooms consistently because its flowers form on new growth. Plants received as *S. bockii* from American nurseries appear to be something else and we received *S. variegata* from an American nursery as *S. acuminata* var. *microphylla*.

Salix waldsteiniana Willd.

Synonyms: *S. arbuscula* 'Erecta'.

Low densely branched shrub similar to *S. arbuscula*, but with more erect habit from European mountains (Alps, Balkans) without particular ornamental features.

Species	**Subgenus**	**Section**
S. nivalis Hooker	*Chamaetia*	*Chamaetia*
S. reticulata L.	*Chamaetia*	*Chamaetia*
S. alatavica Kar.	*Chamaetia*	*Glaucae*
S. arctica Pall	*Chamaetia*	*Glaucae*(Skv) *Diplodictyae* (Argus)
S. brachycarpa Nutt.	*Chamaetia*	*Glaucae*
S. glauca L.	*Chamaetia*	*Glaucae*
S. nakamurana Koidz.	*Chamaetia*	*Glaucae*
S. pyrenaica Gouan.	*Chamaetia*	*Glaucae*
S. pedicellaris Pursh	*Chamaetia*	*Myrtilloides*
S. alpina Scop.	*Chamaetia*	*Myrtosalix*
S. myrsinites L.	*Chamaetia*	*Myrtosalix*
S. saxatilis Turcz.	*Chamaetia*	*Myrtosalix*
S. herbacea L.	*Chamaetia*	*Retusae*
S. polaris Whlnb.	*Chamaetia*	*Retusae*
S. retusa L.	*Chamaetia*	*Retusae*
S. serpyllifolia Scop.	*Chamaetia*	*Retusae*
S. arbuscula L.	*Vetrix*	*Arbuscella*
S. foetida Schleich.	*Vetrix*	*Arbuscella*
S. phylicifolia L.	*Vetrix*	*Arbuscella*
S. waldsteiniana Willd.	*Vetrix*	*Arbuscella*
S. coesia Vill.	*Vetrix*	*Caesia*
S. elaeagnos Scop.	*Vetrix*	*Canae*
S. variegata Franchet	*Vetrix*	*Cheilophilae*
S. reinii Fr.&Sav.	*Vetrix*	*Glabrella*
S. apoda Trautv.	*Vetrix*	*Hastatae*
S. integra Thunb.	*Vetrix*	*Helix*
S. purpurea L.	*Vetrix*	*Helix*
S. candida Fluegge	*Vetrix*	*Lanatae* (Argus) *Villosae* (Skv)
S. lanata L.	*Vetrix*	*Lanatae*
S. caprea L.	*Vetrix*	*Vetrix*
S. cinerea L.	*Vetrix*	*Vetrix*
S. tarraconensis Pau	*Vetrix*	*Vetrix*
S. helvetica Vill.	*Vetrix*	*Villosae*
S. lapponum L.	*Vetrix*	*Villosae*

Table 6.1. Organization of *Salix* species within subgenera and sections following Skvortsov (1968) and Argus (1997).

CHAPTER 7

WILLOW (SALIX L.) SPECIES FOR ECOLOGICAL RESTORATION AND BIOMECHANICAL APPLICATIONS

There is a willow grows aslant the brook

That shows his hoar leaves in the glassy stream . . .

Shakespeare, *Hamlet*.

Introduction

The history of human use of willows predates stone-age technology. In northern continental Europe and the British Isles, as well as in the Pacific northwest of America, willows were the most common structural component of wattle/daub construction for shelter and fencing. Flexible willow branches were also the primary material for basket production (*Salix purpurea*, S.*viminalis* and S.*tiandra* are among the best materials for basketry and furniture). Straight willow branches were used for arrow shafts and fish traps both in Eurasia and North America. Willow also has an ethnobotanical significance: indigenous peoples in North America and Eurasia used willow bark infusions as analgesics. Before synthetic production of aspirin was developed, salicin extracted from *Salix* bark was commercially exploited for at least two centuries.

Recently *Salix* has become increasingly used in environmental restoration work, providing a cost-effective material for stabilization and reclamation of disturbed landscapes, both riparian and upland erosion control, and biomass production. Willows are also being used for interdisciplinary research in creative environmental endeavors combining art, science and technology (Hunter, 1992).

The range of application for willows is expanding with the growing effort to minimize negative impacts and outputs of the constructed environment on local ecosystems. Willows' wide geographical and ecological ranges of distribution and adaptability to extreme conditions promote them in many climatic zones and adverse microsite conditions.

Our objective is to describe multiple opportunities that *Salix* can offer for ecological restoration projects including phytoremediation and bioengineering. We provide brief information about *Salix* diversity and discuss their ecological requirements. We summarize and categorize the current applications based on available studies. Finally, we discuss cultural requirements for successful plant establishment, and specific limitations of the genus that should be considered in planning for mitigation of human impacts on the environment.

The diversity of the genus *Salix* and its importance in regional floras

Salix is an important component of many regional floras (Figure 7.1). In most temperate floras the number of native species of willow outnumbers those of other woody genera, and this underscores the availability of a range of native species for appropriate, site-specific use in environmental projects. The total amount of willow species growing throughout North America is about 106 (Zomleter, 1994). A significant naturalizing effect in the constructed or managed landscape can be achieved by using native species in altered landscapes, and public recognition and acceptance of willows is high.

Ecology

Salix is recognized as a widespread wetland and floodplain genus; it is well adapted and highly competitive in saturated soil conditions. However, many factors affect the distribution of individual willow species, beyond a general requirement for plentiful moisture during germination and early establishment. The autecology of willows includes the strategy of early successional plants colonizing newly opened habitats, especially in riparian zones, and newly opened or early successional upland areas. Suitable conditions for *Salix* growth include man-made habitats such as roadside ditches, abandoned agricultural fields, railroads; old mine tailings, gravel pits (Argus, 1986) as well as recently burned, glaciated (soilless) or flooded areas. Disturbance results in an open community with low competition levels, allowing a temporary increase in the dominance of early colonizers.

Willows are among the most common opportunistic woody species. Early successional status implies certain important adaptations and limitations. Pioneer species often colonize nutrient-limited oligotrophic sites. They can grow in poor, nitrogen-deficient soils such as bogs, sand dunes and river sand and gravel-bars. Symbiotic associations that willows form with mycorrhizal fungi enhance plant growth by providing an additional supply of nutrients. *Salix* species benefit from vesicular-arbuscular endomycorrhizae that utilize phosphorus, as well as ectomycorrhiza that use organic nitrogen (Schramm, 1966; Lodge, 1989).

Pioneer plants annually produce numerous seeds and have an effective systems of seed dispersal for long distance travel, before finding an opening for germination and growth. Seeds of willow are very small and have a specific adaptation—down or small hairs-- for traveling long distances in the air. Establishment in vegetation gaps favors those plants that can tolerate full sunlight, and willows in particular are not tolerant of shade. Common characteristics of early successional plants include high relative growth rate with relatively short life expectancy (Raven, 1992), and willows are no exception.

During different stages of development and growth, *Salix* exhibits 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 (McLeod and McPherson, 1973) because seeds of *Salix* are viable for only a few weeks; 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, 1968). To summarize, the primary factors controlling the native distribution and abundance of species are the availability of moisture for seed germination, an absence of early competitors, and availability of full sunlight.

Ecological differentiation between and within willow species is considerable, and a variety of habitats can be exploited by the same species. The key for their successful use in restoration projects lies with the knowledge and understanding of their biology. Many species are adaptated for growth in heavy, poorly drained (Labrecque et al., 1994) and flooded soils (Krasny et al., 1988); some are considered very drought tolerant, and others are resistant to moderate salinity (Mang and Reger, 1992).

Colonization of disturbed and newly opened sites where *Salix* species may flourish due to their broad adaptability, can accelerate the recovery of damaged ecosystems and the succession into more complex systems. Microclimate changes following the appearance of colonizing willows include an increase of surface shade, increased annual production of leaf debris, and root action and formation of humus, thus improving the soil structure and nutrient status (Stott, 1992). Willows can "anchor" a pioneer community, beginning re-establishment of natural ecological complexity.

Species of *Salix* characterized by particular physiological adaptations, such as morphological plasticity (see Chapters 2) and ecological resilience (see Chapters 6) are predisposed to use in conservation and environmental projects. These include ecosystem restoration (brownfields, refuse dumps, industrial sites, abandoned rights-of-way, etc.) and nature conservation (habitat enhancement), and phytoremediation (including phytoextraction, rhizofiltration and phytostabilization) (Salt et al., 1998), bioengineering and biomass production for both fuel and fiber.

Ecosystem restoration and nature conservation

Ecological restoration of wetlands and wildlife conservation

Perhaps the most important ecological role for *Salix* species relates to their affiliation with wetlands. Wetland 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 current federal wetland policy of "no net loss", based on replacement ("mitigation") of damaged or 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 one of the most effective keystone species for ecological restoration of wetlands, in both structure and function. Willows are most commonly installed in riparian restoration programs (McCreary and Tecklin, 2000), but often as a "nurse crop" for the establishment of larger and longer-lived woody species.

Willows tend to be twiggy and dense and therefore have a high wildlife value, providing food and cover for scores of birds, small mammal and insects (Hightshoe 1998). Willows play an important role in the environment as a source of food for many animals, vertebrates and invertebrates (Sommerville, 1994), mostly as leaf and stem tissue, rather than the seed. Additionally, many invertebrate herbivores (from aphids to caterpillars) feed on willows, and support a large food-web of higher trophic levels. Many animals depend on willow for food and shelter (they provide browse for deer, moose and livestock, and willow wood is a favorite food of beavers (Smith et al., 1978). Where dense and abundant, willows supply rich habitat for diverse fauna and support a high density of breeding bird communities.

Land Reclamation

Because of their ability to bud, root, and resprout from totipotent cells at even very old nodal areas, willows can be successfully used for rapid establishment of plant cover for reclamation projects (White, 1992), in such forms as mats, stakes, rooted cuttings, stumps with rootmasses. *Salix* species can establish on waste grounds even where topsoil is virtually absent, so they are used to reestablish plant cover on environmentally disrupted areas such as industrial spoils, mines and gravel pits (Hartwright, 1960), overburdens, quarries, highly eroded soils, waste sites and roadsides. Willows may eventually colonize open areas naturally (Schramm, 1966; Clewell, 1999), but as with other natural processes this early succession is spatially random and temporally unpredictable. With some assistance at early stages (in the form of seeding or vegetative propagation) restoration can be achieved more quickly. Low cost plantings of *Salix* comply with new reclamation laws in many states and facilitate the process of land rehabilitation by altering microclimate, reducing runoff, providing ecologically diverse wildlife habitats and enhancing human recreational areas.

Afforestation of industrial sites

Due to their ability to tolerate significant concentrations of air and soil pollutants willows are very suitable for planting around industrial sites, both active and abandoned. Many authors cite *Salix* among other woody plants as tolerating urban conditions

(Schmidt, Dirr, Hightshoe 1992). Some authors (e.g., Zvereva, 1997) mention that *Salix,* along with *Betula,* are the only woody species found in those urban areas of Europe with very high air pollution levels. They concluded that long-term and severe pollution by sulphur 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*.

Willows are resistant to soil compaction (Chapter 2) and salinity (Hightshoe, 1998); these qualities can be exploited by planting *Salix* species in cities in naturalized landscape areas using indigenous plant material in the urban environment.

Phytoremediation

Phytoextraction

The recent trend to remediate soils on site is technically and economically preferable to excavation and removal for landfill disposal (Nadeau et al., 2002). Soil bioremediation is still in its experimental phase, but willows show much promise in this area. *Salix* is currently under intensive research scrutiny for its potential for soil remediation involving extraction of heavy metal due to the plants' ability to take up some toxic heavy metals through their roots and effectively transport them to stems or leaves, where they can be removed by harvesting (Dickinson et al., 1994; Landberg and Greger, 1994; Punshon and Dickinson, 1997; Greger and Landberg, 1999).

An attempt to rehabilitate exhausted farmland has been reported from southernmost Sweden, where the cadmium content of wheat grain sometimes exceeds the limits for human consumption. The growing of willow in those fields for one or two rotation periods (a rotation period is normally 24 years) appears to be a promising way of reducing the cadmium content in soil (Perttu and Kowalik, 1997).

Phytodegradation

Some varieties of *Salix* (e.g. S. x'Prairie Cascade') tolerate some petrochemical pollutants, and when planted on blackened soil produced by an oil spill in Wisconsin, have shown excellent growth and capability of cleaning the soil via oil-degrading microbes associated with their roots (Thompson, 1998). Willows have been recommended for recultivation of oil-mining areas by scientists from Siberia (Chralovich, 2000). Instead of covering polluted areas with fresh soil, as was done in the past, degraded areas were planted with willow stakes which soon produced green islands in the taiga. This method allows faster sequestration of pollutants than in previous attempts, where an expensively imported layer of soil covered the polluted areas before herbaceous plants were seeded.

Rhizofiltration and rhizostimulation

The idea of constructed wetlands functioning as purification plants for wastewater is gaining currency in North America and Eurasia. Rhizofiltration, the ability of plants roots to remove pollutants from aqueous solutions, can play an important role in the reduction of excessive nutrients and metals in a stream (Peterson and Teal, 1996).

Vegetation filters based on a free flowing water system with submerged vegetated beds are considered as a potential remedy for improving quality of domestic, municipal wastewater and agricultural runoff. The added value of harvestable biomass, providing necessary lignin for composting operations, is a bonus.

A variety of physical, chemical and biological processes occurring in the rhizosphere help to decrease the pollutant load in water passing through dense aquatic vegetation. Species of genus *Salix* commonly growing along streams and swamp areas have been proposed as essential elements for vegetation filters, which planting led to a substantial reduction of the polluted load (Elowson and Christersson, 1994; Kirt, 1994; Obarska-Pempkowiak, 1994).

The use of *Salix* for purification of waters and soils has been demonstrated in Scandinavia (Perttu and Kowalik, 1997; Ali et al., 1999). Physiological characteristics of *Salix* such as high rates of evapotranspiration (Persson and Lindroth, 1994), efficient nutrient uptake (Ericsson, 1981), tolerance of flooded conditions (Jackson and Attwood, 1996) and high biomass productivity, are crucial for the use of willows for vegetation filters. Wastewater nutrients can benefit biomass plantation, and expand the value of constructed wetlands in utilization of excessive nutrients for cultivation of biomass for energy purposes, or for compost (Perttu, 1993). The levels of irrigation load that provide an adequate supply of nutrients for plant growth and improve the quality of effluent leaving the plot, have been identified (Kowalik and Randerson, 1994), while domestic wastewater appears to be almost an ideal nutrient solution for *Salix* growth (Perttu and Kowalik, 1997).

Phytostabilization

Phytostabilization, is the reduction of pollutants in the environment through absorbtion and adsorbtion to plant roots. The goal is to retain pollutants as close to their source as possible by preventing their dilution and therefore restricting their distribution and secondary pollution of surrounding areas applied in construction of vegetative buffer zones for capping the landfills (Hasselgren, 1994), sewage treatment plants, steelworks (Craven, 1994) and waste dumps. The dense root system can penetrate deep into the soil and explore water rich patches (Schiffer, 1999) along with continuous growth of some species during whole vegetative season (Labrecque et al., 1994). High transpiration rates increase willows' metabolic potential creating an efficient dehydration plant while locking up the pollutants. The establishment of willow vegetative buffer zones can be of great practical use due to their ability to sequester heavy metals and other contaminants in their root systems, halting their circulation within the environment (Ettala, 1988).

Another example of phytostabilization through dehydration of moist substrates is applied to dewatering of sewage and dredging sludge. The technique, called SALIMAT, has been described for dewatering of sludge from the dredging of waterways, that represents an impassable swampy-terrain where traditional planting methods are impossible (De Vos, 1994). The technique uses rolls of willow rods rolled around a central tube, which is 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 will be established in a few months time with relatively low cost, thus providing stabilization of the substratum (Stott et al., 1994).

An intensification of nitrification processes on municipal sewage deposits occur, when planted with *Salix* (Wielgosz, 2000). As a result of high rates of transpiration, a significant reduction in moisture can be quickly achieved while the polluting elements in the sludge apparently do not affect willow growth (Scheirlink et al., 1996). An extensive root system and abundant litter will improve soil structure, promote biotic communities and will create a forest microclimate. Afforestation of sludge field appears to be one of the best solutions by reducing the amount of water that can percolate and pollute the groundwater.

Biological engineering

Water erosion.

Species of *Salix* are often planted to stabilize riverbanks, lakes, ponds, man-made drainages and channels (Bache and MacAskill, 1984; Morgan and Rickson, 1995; Wu, 1995; Lefkowitz, 2002), that are subject to frequent flooding and wave action where control of soil erosion is important factor for improving water quality. As well as providing the mechanical stabilization of slopes, a vegetation cover with continuous mat of fibrous roots can minimize the washing out of soil particles, thus decreasing the level of suspended solids while providing better habitat for microorganisms participating in purification processes**.** Many *Salix* species that are tolerant of flooding were found to be an efficient protection against wave erosion in reservoirs (Morgan and Rickson, 1995). They also cover large areas of bare mud making them less sightly.

The spreading root system of many species, such as *S. exigua* enmeshes the soil, effectively preventing erosion of the banks. It also can be used to stabilize slopes along the highways. Willows proved to be efficient in maintaining a secure slope by depleteing soil moisture via transpiration This is an example of “phreatophyte” vegetation (Gray and Leiser, 1982). Seepage areas can be controlled by willow wattling or brush layering, drying those areas and promoting stabilization (Gray and Leiser, 1982). Some species, when propagated vegetatively, will thrive even on dry sites (Kraebel, 1936).

Techniques of successful establishment and fast effect for erosion control such as by insertion of woody stems into the moist ground, or the application the stems, or woven mats, horizontally using vertical stakes to protect them from rolling down the slope. Because they are long, flexible, easily rooted and almost always available near the site willows are an ideal plant material for the wattling technique: willow bundles laid in shallow trenches and covered with soil.

Wind erosion

Different species of willows can be applied to wind erosion control. An ancient technique for erosion control in the mountains consisted of erecting willow wattle screens on unstable slopes where they are "initially performing a purely mechanical function, and often subsequently root themselves” (FAO, 1979).

Sand stabilization is another problem associated with wind-blown erosion. Some species of *Salix* (*S. humilis*, *S. exigua*, *S. myricoides*) can grow in sandy soils and can be considered tolerant of drought conditions. They survive in critical conditions of harsh wind, poor nutrient levels, low soil moisture content and constantly moving sandy ground (Cowles, 1991). Sand dunes and other unstable surfaces may be stabilized by planting those *Salix* species that tolerate such extreme conditions (Schiechtl, 1980). In Germany willows are used for erosion control on sand hills along highways (Schiffer, 1999).

Windbreaks and living walls

Fast growing species of willows can create efficient and attractive windbreaks that protect agricultural lands and enhance the view of vast landscapes, such as along highways. 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. Willow windbreaks are also effective shelterbelts for trapping snow (Bache and MacAskill, 1984) protecting roads and buildings from snow drifts. Some *Salix* species are recommended for controlling wind erosion and providing shelter on the peat soils with high groundwater table (Morgan, 1995). Living willow walls are becoming popular planted along highway noise retention concrete walls, (Szczukowski et al., 1998) or 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.

Willow windbreaks can be established quite cost effectively by inserting one year old, 2 meter 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 meters tall, which in the following two years will reach 8 m (Stott, 1992). Different species of *Salix* are suitable for this purpose depending on the desired height of the windbreak.

Biofuel production

The use of *Salix* species for energy production is a relatively new area of research and there is evidence that biomass production in willow plantations is higher than in poplar (Perttu, 1993). National programs are developing in Canada and several countries within the European Community (Denmark, Sweden, Finland and the United Kingdom) are designed to maximize productivity, the selection of new superior clones suitable for repeated harvesting and resistance to pests, and the development of management techniques for sustainable agriculture. Willow also appears among the most promising biomass fuel in the USA. Some research projects of willow biomass production have begun and the possibility exists that by 2010 farmers in New York state alone may be growing 50,000 acres of willow for biomass production (Beardsley, 1996).

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” (abandoned polluted industrial sites) and marginal lands. In Northern Ireland where 75% of agricultural land is designated as marginal and where traditional crops are economically unviable due to poor soil and harsh climatic conditions, a significant interest in willow biomass production has developed (Dawson, 1992). Research for the use of willows for biomass plantation as alternative crop in soils contaminated with radioactive caesium conducted in Sweden (Sennerby-Forsse et al., 1993).

The idea of utilizing biofuel (or biomass) energy source as an alternative to fossil fuels, which are responsible for increased carbon dioxide loads in the atmosphere and contributes to global warming, is based on compensation of carbon dioxide uptake during plant growth production and its release during the burning of wood. Biofuel represents an ecologically promising energy resource reducing greenhouse gas levels, acid rain, soil erosion, and water pollution, with additional economic benefits including reduced dependence on foreign oil and improvement of domestic rural economies.

Cultural 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 will increase project success. Far too many manuals and articles merely say “Willow species” or “*Salix* sp.” without further specification. Luckily, most willows do well in cultivation. Requirements for optimum establishment and viability of willow include: planting during dormant period, provision of moist conditions at early stages of germination or rooting, full sun exposure. One or two years of supplemental irrigation and weed control may be necessary during the first year (Sage, 1999). A wide range of soils is suitable for plantings and soil pH is less important in cultivation than in the wild (Stott, 1992). Two or three years are required for willow roots to develop into an extensive system of surface lateral roots or reach the more permanently moist deep soil layers.

The most common practice used for willow plantations in Europe is coppicing (pruning of all apical growth) based on and 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 usually ranges from 3 to 5 years. Coppicing will enhance the branching appearance of willows. Coppiced willows may also support a much higher density of breeding birds (Wilson, 1992).

Although willows are quite easy to grow after they have been established, they still may require minimum care. Periodic inspection and some pruning are beneficial, especially after wind or ice damage. As with other fast growing pioneer species, *Salix* is "weak-wooded" and susceptible to breakage. Damage caused by insects or disease can sometimes cause severe injuries to leaves and stems but rarely causes death of the plant. Planted in shade, willows can become leggy and unattractive, and will be more susceptible to diseases.

Proper siting of plants will help increase their landscape value. 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 develop into their full mature size without overcrowding. Constraints of *Salix* use in urban areas include damage of drainage lines due to roots exploring for water,

damage to foundations, or road and path base layers due to exerting pressure of roots when trees are planted too closely, and lack of ample space for growth of tree species. 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).
In propagation from the wild or from stock, mature willow logs, whips and cuttings can all be used for easy establishment. Nursery stock may be used preferentially especially in areas where weeds and drought are a problem. Unfortunately, the commercial plant supply tends to be limited in the number of species and in quantities available (Chapter 5).

The lack of a variety of native species and misidentification of available plant stock due to taxonomical difficulties of the genus are common problems 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, but their full potential of the genus has to be explored at the species level. Knowledge and understanding of their biology and ornamental features can help to create more effective environmental designs.

Conclusion

Salix is a promising resource in mitigating the impact of environmental degradation and building sustainable biocycling systems. Major environmental challenges can be addressed through installation of groups of native willows. Principals of the environmental applications of *Salix* are based on ease of propagation, rapid growth rate, successful establishment even in difficult environments, utilization of coppicing techniques for rejuvenation and increased biomass production, as well as the ability in certain conditions to start vegetative cover in nutrient deprived soils which later provides a humus layer for following successional stages through their biomass accumulation.

Combined biofuel production and treatment of wastewater and sludge for irrigation are under development in some countries (Perttu, 1993; Riddel-Black, 1994). A model for optimal fertilizing strategies is developing (Hansson et al., 1999), which would fulfill the nutrient requirements of the plants and at the same time prevent high rates of accumulation of contaminants such as heavy metals.

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 and provide habitat for numerous organisms above and below the water level, enhancing visual characteristics. Occasional harvesting of willows supplies material for crafting. Willow branches represent valuable material for artwork and can be implemented into multiple ranges of creative work. Willow stems from a local energy forest can be used for building numerous living willow play structures, serving as a play elements and enhancing school and park environments (Danks, 2002). The integration of willow art into restoration projects – ‘ecological art’ (Lefkowitz, 2002) may afford extensive public support and awareness and make restoration projects entertaining for children (Lambert, 2000).

Multiple human values may be accommodated in a single installation. We hope to continue to develop site specific solutions for addressing environmental concerns in anthropogenically modified landscapes based on multifunctional systems.

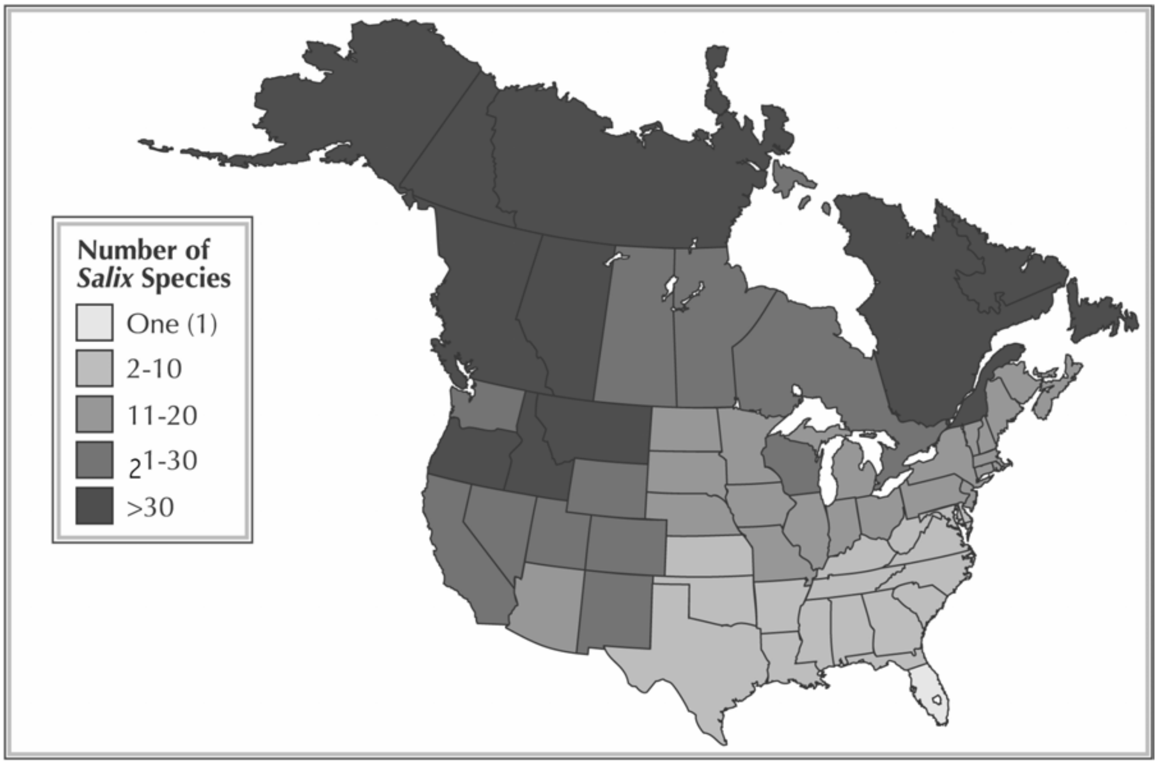


Figure 7.1. *Salix* species diversity in USA and Canada based on regional floras.

CHAPTER 8

CONCLUSIONS

The demonstrated adaptability of the genus *Salix* to different environmental stress factors offers opportunities for its broader use in the constructed landscape, and the study of individual species' ornamental characteristics should extend their horticultural use. The following overall conclusions can be drawn from the foregoing studies and experiments:

1. **Effects of soil compaction and flooding on the growth of 12 *Salix* species**

   - Neither the stresses of soil compaction nor flooding caused significant reduction of growth in *Salix* species, which were able to function successfully under these conditions.

   - The hypothesis that poor soil aeration is the limiting factor to root elongation in high bulk density soils was not confirmed; oxygen exchange between soil and atmosphere continued to be efficient.

   - Considerable differentiation was recorded among species, based on morphological adaptations to flooding; alluvial species exhibited a wider range of morphological adaptations than did species adapted to stagnant soils.

   - Growth strategies for obtaining additional oxygen included exploration of oxygen rich upper level (adventitious root formation, snorkeling roots growing along the water surface), reestablishment of root contact with the atmosphere (roots exhibiting negative gravitropism), and internal oxygen transport from the stem to roots (lenticel hypertrophy, formation of aerenchymatous roots).

- For some species, no morphological changes were recorded. Perhaps the adaptation of *Salix* to growth in hypoxic conditions results from a combination of morphological, anatomical and metabolic responses.

- Accumulation of ethylene in soils occurs under waterlogging conditions and is probably the trigger for morphological changes of *Salix* species.

2. Cadmium and copper uptake and translocation by 5 *Salix* species

-Metal uptake, translocation and growth response varied with the particular metal, the application level and the species.

-The general trend for copper was stimulation of growth at lower (5μM) concentration and considerable depression of growth at high (25 μM) concentration.

- *Salix* species were less sensitive to cadmium than to copper, and plant growth was not inhibited even at high concentration for most willows.

- Analysis of total metal content revealed that metal taken up by the plant goes to the aerial tissues. The greatest cadmium content was found in wood, an intermediate amount in the root, and the least in shoot tissues. The highest copper concentration was found in roots, intermediate in wood and lowest in shoots.

- The copper content of aerial tissues was lower that that of cadmium. Cadmium appears to be more mobile within plants.

3. Differential response of 9 *Salix* species to ozone exposure

- Marked interspecific differences in ozone tolerance was found, based on visible injury in response to a single acute dose.

- As the season progresses ozone injury increased; therefore, tissue age is presumed to increase susceptibility to damage.

- Ozone sensitive (*S. hastata*) and ozone-tolerant (*S. humilis*) species were documented.

4. Horticultural evaluation of *Salix* species

- The horticultural evaluation of *Salix* species resulted in the recommendation of 20 species and cultivars with the potential for florist cut-stem production, and 60 taxa suitable for alpine and small urban gardens.

- Ornamental potential and performance in the continental conditions of the Midwest for those species were assessed. For all species, taxonomy and provenance were elucidated, and species descriptions were prepared.

5. **Practical applications of *Salix* species for environmental control and ecological restoration**

- *Salix* is a promising resource in mitigating the impacts of environmental degradation, and preventing soil loss in both urban and agroecosystems.

- Current environmental applications for which *Salix* species are recommended can be categorized into several broad areas including ecosystem restoration and nature conservation (restoration of wetlands, land reclamation, afforestation of industrial sites); phytoremediation (phytoextraction, phytodegradation, rhizofiltration, rhizostimulation and phytostabilization); bioengineering (water and wind erosion control, construction of windbreaks and living walls); and biomass production.

APPENDIX

Salix species observed during the study:

S. acutifolia
S. alatavica
S. alba ‘Aurea’
S. alba ‘Britzensis’
S. alba ‘Cardi nalis’
S. alba ‘Drakenburg’
S. alba ‘Sericea’
S. alba ‘Tristis’
S. alba ‘Vitellina’
S. alba ‘Vitellina Nova’
S. alpicola
S. alpina
S. amplexicaulis
S. amygdaloides
S. apennina
S. arbuscula
S. aurita
S. babylonica ‘Crispa’
S. babylonica ‘Navaho’
S. babylonica ‘Umbraculifera’
S. bakko
S. bebbiana
S. bothii
S. borealis x *islandica*
S. brachycarpa ‘Blue Fox’
S. brevipens
S. breweri
S. coesia
S. candida
S. cantabrica
S. caprea
S. caprea’Pendula’
S. caprea ‘Boston Fen’
S. caprea x *lasiolepis*
S. caroliniana

S. caspica
S. chaenomeloides
S. chilensis
S. cinerea
S. cinerea 'Tricolor'
S. commutata
S. coriacea
S. daphnoides
S. daphnoides var.*latifolia*
S. dasyclados
S. discolor
S. drummondiana
S. elaeagnos
S. eriocephala
S. exigua
S. fargesii
S. fluviatilis 'Multnomah'
S. foetida
S. fragilis
S. fragilis 'Bullata'
S. geyeriana
S. glabra
S. glauca
S. glaucosericea
S. goddingii
S. gracilistyla
S. gracilistyla 'Melanostachys'
S. gracilistyla 'Hagensis'
S. hastata
S. hastata 'Wehrhahnii'
S. helvetica
S. hibernica
S. hindsiana
S. hookeriana
S. houghtonii
S. humilis
S. hungarica
S. integra
S. integra 'Hakuro Nishiki"
S. integra 'Pendula'

S. islandica
S. jessoensis
S. koriyanagi
S. laggeri
S. lanata
S. lanata 'Mark Postill'
S. lanceolata
S. lapponum
S. lapponum 'Grayii'
S. lasiandra
S. lasiandra 'Nehalem'
S. lasiolepis 'Rogue'
S. lindleyana
S. lucida
S. maccaliana
S. mackensiana
S. magnifica
S. medwedewii
S. mielichhoferi
S. miyabeana
S. myricoides
S. myrsinifolia
S. myrsinites
S. nakamurana
S. neotricha
S. nigra
S. paradoxa
S. pedicellaris
S. pentandra
S. pentandra 'Patent Lumley'
S. petiolaris
S. phylicofolia
S. phylicofolia 'Strandir'
S. pierotii
S. pseudomedemii
S. pseudopentandra
S. purpurea 'Blue Canyon'
S. purpurea 'Dicki Meadows'
S. purpurea 'Eugene'
S. purpurea 'Nana'

S. purpurea ‘Pendula’
S. purpurea ‘Richartii’
S. purpurea ‘Streamco’
S. pyrenaica
S. pyrolifolia
S. reinii
S. repens
S. repens ‘Bergen’
S. repens ‘Boyd’s Pendulous’
S. repens ‘Iona’
S. repens ‘Voorthuizen’
S. rosmarinifollia
S. saxatilis
S. schwerinii
S. scouleriana
S. sericea
S. serpyllifolia
S. silesiaca
S. sitchensis
S. starkeana
S. subopposita
S. tarraconensis
S. triandra
S. tsugaluenis ‘Ginme’
S. udensis ‘Sekka’
S. variegata
S. viminalis
S. waldsteiniana
S. x*wimmeriana*
S. ‘Austree Hybrid’
S. x*balfourii*
S. x*calliantha*
S. x*cashmiriana*
S. x’Flame’
S. x*forbyana*
S. xgillotii
S. x’Golden Curls’
S. x*hirtei*
S. x*molissima*
S. x*meyeriana*

S. x'Prairie Cascade'
S. x'Scarlet Curls'
S. x'Snake'

REFERENCES CITED

Abeles, F.B., P.W.Morgan and M.E.Saltveit. 1992. Ethylene in plant biology. Second edition. Academic Press, Inc.

Ali, M.B., R.D.Tripathi, U.N.Rai, A.Pal and S.P.Singh. 1999. Phisoco-chemical characteristics and pollution level of lake Nainital (U.P., India): role of macrophytes and phytoplankton in biomonitoring and phytoremediation of toxic metal ions. Chemosphere 39(12): 2171-2182.

Allen, S.E., 1989. Editor. Chemical Analysis of Ecological Materials. Blackwell Scientific, Oxford.

Argus, G.W. 1986. The genus *Salix* (*Salicaceae*) in the Southeastern United States. Systematic Botany Monographs 9: 170 p.

Argus, G.W.1997. Infrageneric classification of *Salix* (*Salicaceae*) in the New World. Systematic Botany Monographs 52:121p.

Argus, G.W., C.L.McJannet and M.J.Dallwitz, 1999. *Salicaceae* of the Canadian Arctic Archipelago: Descriptions, Illustrations, Identification, and Information Retrieval. Version: 2nd November 2000. http://www.mun.ca/biology/delta/arcticf/.

Armstrong, W. 1964. Oxygen diffusion from the roots of some British bog plants. Nature 204: 801-802.

Armstrong, W. 1968. Oxygen diffusion from the roots of woody species. Physiologia Plantarum, vol.21, p.539-543.

Armstrong, W. 1979. Aeration in higher plants. In H.W.Woolhouse (Ed.). Advances in botanical research. Volume 7: 226-332.

Armstrong, W., R.Brandle and M.B.Jackson. 1994. Mechanisms of flood tolerance in plants. Acta Bot.Neerl. 43(4), December: 307-358.

Bache, D.H. and I.A.MacAskill. 1984. Vegetation in civil and landscape engineering. Granada Publishing, London, Toronto, Sydney, New York. 317 p.

Baker, A.J.M., 1981. Accumulators and excluders – strategies in the response of plants to heavy metals. Journal of Plant Nutrition 3: 643-654.

Baker, A.J.M., Brooks R.R., Reeves R. 1988. Growing for gold…and copper…and zinc. New Sci.117: 44-48.

Baker, A.J.M. 1993. Cadmium sensitivity and constitutive resistance. In Methods in comparative plant ecology. Ed.G.A.F.Hendry and J.P.Grime. University of Sheffield, UK.

Beardsley, T. 1996. Bring Me a Shrubbery. Scientific America 11: 20.

Berrang, P., D.F.Karnosky and J.P.Bennett. 1991. Natural selection for ozone tolerance in *Populus trenuloides*: an evaluation of nationwide trends. Can.J.For.Res. 21: 1091-1097.

Carlson, M. 1950. Nodal adventitious roots in willow stems of different ages. Am J.of Botany. Vol.37, July: 555-561.

Chralovich E. 2000. Vtoraya zizn "mertvoy semli". Lesnoe chozaystvo 6: 26 [In Russian].

Clewell, A.1999. Restoration of riverine forest at Hall Branch on phosphate-mined land, Florida. Restoration Ecology 7(1): 1-14.

Cowles, H.C. 1991. The ecological relations of the vegetation on the sand dunes of lake Michigan. Pages 28-55 in Foundations of Ecology. Published in association with The Ecological Society of America. The University of Chicago press, Chicago & London.

Craul, P.J. 1985. A description of urban soils and their desired characteristics. J.Arboriculture 11: 330-339.

Crawford, RMM. 1992. Oxygen availability as an ecological limit to plant distribution. Advances in Ecological Research 23: 93-185.

Craven, D.R.J. 1994. Hallside steelworks project. Pages 169-172 in P.Aronsson and K.Perttu, editors. Willow vegetation filters for municipal wastewater and sludges. Swedish University of Agricultural Sciences, Uppsala.

Crawford, RMM. 1992. Oxygen availability as an ecological limit to plant distribution. Advances in Ecological Research 23: 93-185.

Cunningham, S.D. and W.R.Berti. 1993. Remediation of contaminated soils with green plants: an overview. In Vitro Cell.Dev.Biol. 29P: 207-212.

Danks, S.G. 2002. Green Mansions. Landscape Architecture 6: 38-43, 93-94.

Dawson, M. 1992. Some aspects of the development of short-rotation coppice willow for biomass in Northern Ireland. Pages 193-206 in R.Watling and J.A.Raven, editors. 1992 Willow Symposium. Proceedings of The Royal Society of Edinburg. Vol.98. Published by The Royal Society of Edinburg, Edinburg.

Day, S.D., N.L.Bassuk and H.van Es.1995. Effect of four compaction remediation methods for landscape trees on soil aeration, mechanical impedance and tree establishment. J.Environ.Hort. 13(2): 64-71.

Denny, H.J. and D.A.Wilkins 1987. Zinc tolerance in *Betula* spp. New Phytol. 106: 545-553.

De Vos, B. 1994. Using the SALIMAT technique to establish a willow vegetation cover on wet substrates. Pages 175-181 in P.Aronsson and K.Perttu, editors. Willow vegetation filters for municipal wastewater and sludges. Swedish University of Agricultural Sciences. Uppsala.

Dickinson, N.M., T.Punshon, R.B.Hodkinson and N.W.Lepp, 1994. Metal tolerance and accumulation in willows. Pages 121-127 in P.Aronsson and K.Perttu, editors. Willow vegetation filters for municipal wastewater and sludges. Swedish University of Agricultural Sciences, Uppsala.

Dorn, R.D. 1976. A synopsis of American *Salix*. Can.J.Bot. 54: 2769-2789.

Ettala, M. 1988. Evapotranspiration from *Salix aquatica* plantation at a sanitary landfill. Aqua fennica 18(1): 3-14

Elowson, S. and L.Christersson. 1994. Pages 219-223 in P.Aronsson and K.Perttu, editors. Willow vegetation filters for municipal wastewater and sludges. Swedish University of Agricultural Sciences, Uppsala.

Eltrop, L., G.Brown, O.Joachim and K.Brinkmann. 1991. Lead tolerance of *Betula* and *Salix* in the mining area of Mechernich/ Germany. Plant and Soil 131: 275-285.

Encyclopedia of garden plants, 1992. Ed.C.Brickell. Macmillan, USA.

Ericsson, T. 1981. Growth and nutrition if three *Salix* clones grown in low conductivity solutions. Physiologia Plantarum 52: 239-244.

FAO, 1979. Poplar and Willows in wood production and land use. Forestry Series #10.

Flora of Japan by Jusaburo Ohwi, 1965. Smithonian Institution, Washington D.C., p.363.

Fredericksen, T.S., B.J.Joyce, J.M.Skelly, K.C.Steiner, T.E.Kolb, K.B.Kouterick, J.E.Savage and K.R.Snyder. 1995. Physiology, morphology, and ozone uptake of leaves of black cherry seedlings, saplings, and canopy trees. Environmental Pollution. 89(3): 273-283.

Glinski, J. and J.Lipiec. 1990. Soil physical conditions and plant roots. CRC Press, Inc., Florida.

Greeger, M. and S.Lindberg, 1986. Effects of Cd 2+ and EDTA on young sugar beets (*Beta vulgaris*). I. Cd $^{2+}$ uptake and sugar accumulation. Physiol.Plant.66: 69-74.

Greger, M. and T.Landberg, 1999. Use of willow in phytoextraction. International Journal of phytoremediation 1(2): 115-123.

Grimshaw, H.M., S.E.Allen and J.A.Parkinson, 1989. Nutrients elements. Pages 81-159 in S.E. Allen, editor. Chemical Analysis of Ecological Materials. Blackwell Scientific, Oxford.

Hansson, P.-A., S-E.Svensson, F.Hallefalt, H.Diedrichs. 1999. Nutrient and cost optimization of fertilizing strategies for Salix including use of organic waste products. Biomass &Bioenergy 17: 377-387.

Hasselgren, K. 1994. Landfill leachate treatment in energy forest plantations. Pages 215-217 in P.Aronsson and K.Perttu, editors. Willow vegetation filters for municipal wastewater and sludges. Swedish University of Agricultural Sciences, Uppsala.

Hartwright, T.U. 1960. Planting trees and shrubs in gravel working. Sand and gravel assocoation of Great Britain, London.

Heath, R.L. and G.E.Taylor Jr. 1997. Physiological processes and plant responses to ozone exposure. Pages 317-369 in H.Sandermann, A.R.Wellburn and R.L.Heath (Eds.). Forest decline and ozone. Springler.

Hightshoe, G. 1998. Native trees, shrubs and vines for urban and rural America. John Wiey & Sons, Inc, New York, Chichester, Weinheim, Brisbane, Singapore, Toronto.

Hill, A.C., H.E.Heggestad and S.N.Linzon. 1970. Ozone. Pages B1-B6 in J.S.Jacobson and A.C.Hill (Eds.). Recognition of Air Pollution injury to vegetation: a pictorial atlas. Air Pollution Control Association. Pittsburgh, Pennsylvania.

Hogstad, O., 1996. Accumulation of cadmium, copper and zink in the liver of some passerine species wintering in Central Norway. The Science of the Total Environment 18: 275-285.

Hook, D.D., C.L.Brown, P.P.Kormanik. 1970. Lenticel and water root development of swamp tupelo under various flooding conditions. Bot.Gaz.131(3): 217-224.

Hunter, I. 1992. The creative, economic and environmental applications of willow. Page 233 in R.Watling and J.A.Raven, editors. Willow Symposium. Proceedings of The Royal Society of Edinburg. Vol.98. Published by The Royal Society of Edinburg, Edinburg.

International Code of Nomenclature of Cultivated Plants, 1995. Editor P.Trehane. Quarterjack publishing, Wimborne, UK.

Jackson, M.B. and P.A.Attwood. 1996. Roots of willow (*Salix viminalis*) show marked tolerance to oxygen shortage in flooded soils and in solution culture. Plant and Soil 187: 37-45.

Kahle, H., 1993. Response of roots of trees to heavy metals. Environmental and experimental Botany 33(1): 99-119.

Karnosky, D.F., Z.E.Gagnon and D.D.Reed, 1992. Growth and biomass allocation of symptomatic and asymptomatic Populus tremuloides clones in response to seasonal ozone exposures. Can.J.For.Res.22: 1785-1788.

Karnosky, D.F., Z.E.Gagnon, R.E.Dickson, M.D.Coleman, E.H.Lee and J.G.Isebrands. 1996. Changes in growth, leaf abscission, and biomass associated with seasonal tropospheric ozone exposures of *Populus tremuloides* clones and seedlings. Can.J.For.Res. 26: 23-37.

Kawase, M. 1981. Anatomical and morphological adaptation of plants to waterlogging. HortScience 16: 30-33.

Kaye, R.1972. Dwarf Willows. American Rock Garden Society Bulletin 30(1): 1-6.

Kirt, E. 1994. Vegetation filter experiment in Estonia. Pages 79-82 in P.Aronsson and K.Perttu, editors. Willow vegetation filters for municipal wastewater and sludges. Swedish University of Agricultural Sciences, Uppsala.

Koch, J.R., A.J.Scherzer, S.M.Eshita and K.R.Davis. 1998. Ozone sensitivity in hybrid poplar is correlated with a lack of defense-gene activation. Plant Physiol.118: 1243-1252.

Korner, Ch.1999. Alpine plants: stressed or adapted? Pages 297-311 in M.Press, J.Scholes, M.Barker, editors. Physiological Plant Ecology. Blackwell Science.

Kowalik, P.J.and P.F.Randerson, 1994. Nitrogen and phosphorus removal by willow stands irrigated with municipa; waste water – a review of the polish experience. Biomass and Bioenergy 6(1/2): 133-139.

Kozlov, M.V., E.Haukioja, A.V.Bakhtiarov and D.N.Stroganov. 1995. Heavy metals in birch leaves around a nickel-copper smelter at monchegorsk, Northwestern Russia. Environmental Pollution 90: 291-299.

Kraebel, C.J. 1936. Erosion control on mountain roads. *Circ*. 380. USDA, Washington, D.C. 44.

Krasny, M.E., J.C. Zasada and K.A.Vogt. 1988. Adventitious rooting of four *Salicaceae* species in response to a flooding event. Can.J.Bot. 66: 2597-2598.

Krussmann, G. 1985. Manual of Cultivated broad-leaved trees and shrubs. Timber Press. Portland, Oregon.

Labrecque, M., T.I.Teodorescu and S.Daigle. 1994. Effect of sludge application on early development of two *Salix* species: productivity and heavy metals in plants and soil solution. Pages 157-165 in P.Aronsson and K.Perttu, editors. Willow vegetation filters for municipal wastewater and sludges. Swedish University of Agricultural Sciences, Uppsala.

Lambert, A.M. and M.R.Khosla. 2000. Environmental art and restoration. Ecological Restoration. 18:2:109-114.

Landberg, T. and M.Greger, 1994a. Can heavy metal tolerant clones of *Salix* be used as vegetation filters on heavy metal contaminated land? Pages 133-144 in P.Aronsson and K.Perttu, editors. Willow vegetation filters for municipal wastewater and sludges. Swedish University of Agricultural Sciences, Uppsala.

Landberg, T. and M.Greger, 1994b. Cadmiun tolerance in *Salix*. Biologia Plantarum 361 (Suppl.): 280.

Langebartels, C., D.Ernst, W.Heller, C.Lutz, H.-D.Payer and H.Sandermann Jr., 1997. Ozone responses of trees: results from controlled chamber exposures at the GSF Phytotron. Pages 163-200 in H.Sandermann, A.R.Wellburn and R.L.Heath (Eds.). Forest decline and ozone. Springler.

Lanner, R.M. 1976. Patterns of shoot development in *Pinus* and their relationship to growth potential. Pp. 223-243 in “Tree physiology and yield improvement” (M.G.R.Cannell and F.T.Last eds.) Academic Press, London, New York, San Francisco.

Lee, J.A.1999. Arctic plants: adaptations and environmental change. Pp.313-329 in Physiological Plant Ecology. Ed.M.Press, J.Scholes, M.Barker. Blackwell Science.

Lefkowitz, F. 2002. The artists's way to save the earth. Body and soil July-August: 60-63, 90.

Lodge, D.J. 1989. The influence of soil moisture and flooding on formation of VA-endo- and ectomycorrhizae in *Populus* and *Salix*. Plant and Soil 117: 243-253.

Lorenzini, G., L.Guidi, C.Nali and G.F.Soldatini. 1999. Quenching analysis in *Poplar* clones exposed to ozone. Tree Physiology 19: 607-612.

Mang, F.W.C. and Reher R. 1992. Land restoration programmes. Page 244 in R.Watling and J.A.Raven, editors. Willow Symposium. Proceedings of The Royal Society of Edinburg. Vol.98. Published by The Royal Society of Edinburg , Edinburg.

Marczynski, S. 1998. Top Grafting of *Salix*. IPPS 48: 337-341.

Marczynski, S. 2000. Getting wind of the Willows. American Nurserymen July 15: 44-52.

McCreary, D.D. and J.Tecklin. 2000. Homemade dibble facilitates planting willow and cottonwood cuttings. Native plant Journal 1(1): 59-60.

McLeod, K.W. and J.K.McPherson. 1973. Factors limiting the distribution of *Salix nigra*. Bull. Torrey Bot. Club.100: 102-110.

Miller, P.R., M.J.Arbaugh and P.J.Temple, 1997. Ozone and its known and potential effects on forests in Western United States. Pages 39-68 in H.Sandermann, A.R.Wellburn and R.L.Heath (Eds.). Forest decline and ozone. Springler.

Mitsch, W.J., X.Wu, R.Nairn, P.Weihe, N.Wang, R.Deal and C.E.Boucher. 1998. Creating and Restoring Wetlands. BioScience 48(12): 1019-1030.

Moggi, G. 1985. The Macdonald encyclopedia of alpine flowers. Macdonald. 384 p.

Morgan, R.P.C., 1995. Wind erosion control. Pages 191-220 in R.P.C.Morgan and R.J.Rickson, editors. Slope stabilization and erosion control: a bioengineering approach. E &FN Spon, London.

Morgan, R.P.C.and R.J.Rickson, 1995.Water erosion control. Pages 133-190 in R.P.C.Morgan and R.J.Rickson, editors. Slope stabilization and erosion control: a bioengineering approach. E &FN Spon, London.

Musselman, R.C. and B.A.Hale, 1997. Methods for controlled and field ozone exposures of forest tree species in North America. Pages 277-316 in H.Sandermann, A.R.Wellburn and R.L.Heath (Eds.). Forest decline and ozone. Springler.

Nadeau, R.J., S.C.Fredericks and J.L.Brown, 2002. Using native species at superfund sites: the Tonolli metal site project. Land and Water: July/August 2002: 29-32.

Newsholme, C. 1992. Willows, the Genus *Salix*. Timber Press:Portland, Oregon.

Nissen, L.R. and N.W.Lepp, 1997. Baseline concentrations of copper and zinc in shoot tissues of a range of *Salix* species. Biomass and Bioenergy 12 (2): 115-120.

Obarska-Pempkowiak, H. 1994. Application of willow and reed vegetation filters for protection of a stream passing through a zoo. Pages 59-68 in P.Aronsson and K.Perttu, editors. Willow vegetation filters for municipal wastewater and sludges. Swedish University of Agricultural Sciences, Uppsala.

Ohlson, M. and H.Staaland. 2001. Mineral diversity in wild plants: benefits and bane for moose. Oikos 94: 442-454.

Ostman, G. 1994. Cadmium in *Salix* – a study of the capacity of *Salix* to remove cadmium from arable soils, In Willow Vegetation Filters for Municipal Wastewater and Sludges – A Biological Purification System. Proceedings of a conference. pp.133-144.

Pell, E.J., J.P.Sinn, B.W.Brendley, L.Samuelson, C.Vinten-Johansen, M.Tien and J.Skillman. 1999. Differential response of four tree species to ozone-induced acceleration of foliar senescence. Plant, Cell and Environment 22:779-790.

Persson, G. and A.Lindroth. 1994. Simulating evaporation from short –rotation forest: variations within and between seasons. Journal of Hydrology: 156, 21-45.

Perttu, K., 1993. Biomass production and nutrient removal from municipal wastes using willow fegetation filters. Journal of Sustainable Forestry 1(3): 57-70.

Perttu, K.L. and P.J.Kowalik, 1997. *Salix* vegetation filters for purification of water and soils. Biomass and Bioenergy 12(1): 9-19.

Peterson, S.B. and J.M.Teal, 1996. The role of plants in ecologically engineered wastewater treatment systems. Ecological Engineering 6: 137-148.

Polunin, O. and A.Stainton, 1984. Flowers of the Himalaya. Oxford University Press, p.382.

Punshon, T., and N.Dickinson. 1997. Acclimation of *Salix* to metal stress. The New Phytologist 137: 303-314.

Quigley, M.F. 2003. Tree growth and condition in a Midwestern urban park reflects 150 yeas of soil compaction. Urban Ecosystems (in review).

Raven, J.A. 1992. The physiology of *Salix*. Pages 49-62 in R.Watling and J.A.Raven, editors. 1992 Willow Symposium. Proceedings of The Royal Society of Edinburg. Vol.98. Published by The Royal Society of Edinburgh , Edinburgh.

Riddell-Black, D.1994. Heavy metal paper Heavy metal uptake by fast growing willow species, In Willow Vegetation Filters for Municipal Wastewater and Sludges – A Biological Purification System. Proceedings of a conference. pp.145-151.

Riddell-Black, D. 1994. Sewage sludge as a fertilizer for short rotation energy coppice. Pages 91-100 in P.Aronsson and K.Perttu, editors. Willow vegetation filters for municipal wastewater and sludges. Swedish University of Agricultural Sciences, Uppsala.

Sage, R.B. 1999. Weed competition in willow coppice crops: the cause and extent of yield losses. Weed Research 39: 399-411.

Salt, D.E., R.C.Prince, I.J.Pickering and I.Raskin. 1995. Mechanisms of Cadmium mobility and accumulation in Indian Mustard. Plant Physiol. 109: 1427-1433.

Salt, D.E., R.D.Smith, and I.Raskin. 1998. Phytoremediation. Annual Reviews 16-18: 643-668.

Samuelson, L.J. and G.S.Edwards. A comparison of sensitivity to ozone in seedlings and trees of *Quercus rubra* L. New Phytol. 125: 373-379.

Sandermann, Jr., H.A.R.Wellburn and R.L.Heath, 1997. Forest decline and ozone: synopsis. Pages 369-378 in H.Sandermann, A.R.Wellburn and R.L.Heath (Eds.). Forest decline and ozone. Springler.

Scheirlink, H., N. Lust & L.Nachtergale. 1996. Transpiration of two willow species (*Salix viminalis* and *Salix triandra*) growing on a landfill of dredged sludge. Silva Gandavensis 61: 33-45.

Schiechtl, H. 1980. Bioengineering for land reclamation and conservation. The University of Alberta press, Edmonton.

Schiffer, von Rudilf. 1999. Silberweide. Baum-Zeitung 1: 22-25.

Schmidt, G.1992. New Plants from Hungary Tolerating Urban Conditions. International Plant Propagator Society 42:140-142.

Schramm, J.R. 1966. Plant colonization studies on black wastes from anthracite mining in Pennsylvania. Trans.Amer.Phil.Soc. N.S. 56:6-194.

Sennerby-Forsse, L., J.Melin, K.Rosen and G.Siren, 1993. Uptake and distribution of radiocesium in fast-growing *Salix viminalis* L. Journal of Sustainable Forestry 1(3): 93-103.

Sennerby-Forsse, L .1994. The Swedish energy forestry programme. Pages 19-22 in P.Aronsson and K.Perttu, editors. Willow vegetation filters for municipal wastewater and sludges. Swedish University of Agricultural Sciences, Uppsala.

Skelly, J.M., A.H.Chappelka, J.A.Laurence and T.S.Fredericksen, 1997. Ozone and its known and potential effects on forests in Eastern United States. Pages 69-94 in H.Sandermann, A.R.Wellburn and R.L.Heath (Eds.). Forest decline and ozone. Springler.

Skvortsov, A.K. 1968. Willows of the USSR. Nauka. Moscow. [In Russian]. 262 p.

Smith, F.F., D.K.Smith and G.W.Argus. 1978. Willows for pleasure and benefit. American Hort. 57(2): 22-25, 32.

Sommerville, A.H.C.1992. Willows in the environment. Pages 215-225 in R.Watling and J.A.Raven, editors. 1992 Willow Symposium. Proceedings of The Royal Society of Edinburg. Vol.98. Published by The Royal Society of Edinburg, Edinburg.

Stockwell, W.R., G.Kramm, H.-E. Scheel, V.A.Mohnen and W.Seiler. 1997. Ozone formation, destruction and exposure in Europe and the United States. Pages 1-38 in H.Sandermann, A.R.Wellburn and R.L.Heath (Eds.). Forest decline and ozone. Springler.

Stott, K.G.1992. Willows in the service of man. Pages 169-182 in R.Watling and J.A.Raven, editors. 1992 Willow Symposium. Proceedings of The Royal Society of Edinburg. Vol.98. Published by The Royal Society of Edinburg , Edinburg.

Stott, K.G., B.deVos and F.deVos. 1994. Stabilization of silt ponding lagoons with willows using the SALIMAT technique. Pages 229-230 in in R.Watling and J.A.Raven, editors. 1992 Willow Symposium. Proceedings of The Royal Society of Edinburg. Vol.98. Published by The Royal Society of Edinburg, Edinburg.

Summer, J.E. d M.B.Jackson. 1994. Anaerobic conditions strongly promote extension by stems of overwintering tubers of *Potamogeton pectinatus* L. J. Exper.Botany. Vol.45, No. 278: 1309-1318.

Szczukowski, S., J.Tworkowskii, M.Wiwart, 1998. Application of bush willow (*Salix* sp.) in environment shaping and protection. Postepy Nauk Volniczych: 4: 17-24.

Talbot, R. and Etherington J. 1987. Comparative studies of plant growth and distribution in relation to waterlogging. Part X111.The effect of Fe2+ on photosynthesis and respiration of *Salix caprea* and *S. cinerea* spp.*oleifolia*. New Phytol.105: 575-583.

Tang, Z. and T.Kozlowski. 1984. Ethylene production and morphological adaptations of woody plants to flooding. Can.J.Bot. 62: 1659-1664.

Thompson, W. 1998. Botanical Remedies. Landscape Architecture 8: 38-43.

Tingey, D.T. 1989. Bioindicators in air pollution research – applications and constrains. Pages 73-80 in Biologic markers of air-pollution stress and damage in forests. National Academy Press. Washington, D.C.

Turner, A.P. and N.M.Dickinson. 1993. Survival of Acer pseudoplatanus (sycamore) seedlings on metalliferous soils. New Phytol. 123: 509-521.

Watson, C., I.D.Pulford and D.Riddell-Black. 1999. Heavy metal toxicity responses of two willow (*Salix*) varieties grown hydroponically: development of a tolerance screening test. Environmental Geochemistry and Health 21: 359-364.

Wellburn, A.R., J.D.Barnes, P.W.Lucas, A.R.McLeod and T.A.Mansfield. 1997. Controlled O_3 exposures and field observations of O_3 effects in the UK. Pages 201-248 in H.Sandermann, A.R.Wellburn and R.L.Heath (Eds.). Forest decline and ozone. Springler.

White, J.E.J. 1992. Ornamental uses of willow in Britain. Pages 183-192 in R.Watling and J.A.Raven, editors. 1992 Willow Symposium. Proceedings of The Royal Society of Edinburg. Vol.98. Published by The Royal Society of Edinburg , Edinburg.

Wielgosz, E. 2000. Aktywnosc biochemiczna w osadach posciekowych poddanych czteroletniej transformacji roslinnej. Annales Universitatis Mariae Curiie-Sklodowska LV20:185-193 [Summary in English].

Wilson, J. 1992. The breeding bird community of managed and unmanaged willow scrub at Leighton Moss, Lancashire. Pages 207-213 in R.Watling and J.A.Raven, editors. 1992 Willow Symposium. Proceedings of The Royal Society of Edinburg. Vol.98. Published by The Royal Society of Edinburg, Edinburg.

Wu, T.H. 1995. Slope stabilization. Pages 221-264 in R.P.C.Morgan and R.J.Rickson, editors. Slope stabilization and erosion control: a bioengineering approach. E &FN Spon, London.

Zomleter, W.B. 1994. Guide to Flowering Plant Families. The University of North Carolina Press, Chapel Hill & London.

Zvereva, E., M.Kozlov, and E.Haukioja. 1997. Stress responses of *Salix borealis* to pollution and defoliation. Journal of Applied Ecology 34:1387-1396.