

SELECTING AND UTILIZING *POPULUS* AND *SALIX* FOR LANDFILL COVERS: IMPLICATIONS FOR LEACHATE IRRIGATION

Ronald S. Zalesny Jr. and Edmund O. Bauer

USDA Forest Service, Northern Research Station, Institute for Applied Ecosystem Studies, Rhinelander, Wisconsin, USA

The success of using Populus and Salix for phytoremediation has prompted further use of leachate as a combination of irrigation and fertilization for the trees. A common protocol for such efforts has been to utilize a limited number of readily-available genotypes with decades of deployment in other applications, such as fiber or windbreaks. However, it may be possible to increase phytoremediation success with proper genotypic screening and selection, followed by the field establishment of clones that exhibited favorable potential for clean-up of specific contaminants. There is an overwhelming need for testing and subsequent deployment of diverse Populus and Salix genotypes, given current availability of clonal material and the inherent genetic variation among and within these genera. Therefore, we detail phyto-recurrent selection, a method that consists of revising and combining crop and tree improvement protocols to meet the objective of utilizing superior Populus and Salix clones for remediation applications.

Although such information is lacking for environmental clean-up technologies, centuries of plant selection success in agronomy, horticulture, and forestry validate the need for similar approaches in phytoremediation. We bridge the gap between these disciplines by describing project development, clone selection, tree establishment, and evaluation of success metrics in the context of their importance to utilizing trees for phytoremediation.

KEY WORDS: phyto-recurrent selection, phytoremediation, poplar, willow, short rotation woody crops

INTRODUCTION

Leachate disposal for traditional landfill systems includes capping the landfill at the completion of filling, collecting the leachate, and transporting the leachate to treatment facilities. In contrast, establishing landfill covers with trees and/or grasses supports onsite leachate remediation, whereby the leachate is used as fertigation for the plants (Erdman and Christenson, 2000; Wong and Leung, 1989). There are economical and environmental benefits to using short-rotation woody crops for landfill covers and similarly-contaminated sites (Glass, 1999; Isebrands and Karnosky, 2001). Trees belonging to the genera *Populus*

Table 1 Studies testing *Populus* and *Salix* for phytoremediation of various contaminants**Landfill Leachate**

Boye, 2002; Erdman and Christenson, 2000; Zalesny and Bauer, 2007; Zalesny *et al.*, 2007a
Zalesny *et al.*, 2006

Heavy Metals

Bañuelos *et al.*, 1999; Boye, 2002; Eriksson and Ledin, 1999; Greger and Landberg, 1999, 2001;
Klang-Westin and Eriksson, 2003; Landberg and Greger, 1994, 1996; Luyssaert, Van Meirvenne, and Lust,
2001; Punshon and Dickinson, 1997; Sander and Ericsson, 1998; Schnoor, 2000

Municipal Wastes/Dairy-Farm Effluent

Hasselgren, 1998; Perttu, 1993; Perttu and Kowalik, 1997; Roygard *et al.*, 2001

Sludges

Campbell, Zhang, and Tripepi, 1995; Labrecque, Teodorescu, and Daigle, 1998; Moffat, Armstrong, and
Ockleston, 2001

Fertilizers/Pesticides/Nitrates

Burken and Schnoor, 1996, 1997, 1998; Gatliff, 1994; O'Neill and Gordon, 1994

Explosives

Sealock, 2002; Thompson, Ramer, and Schnoor, 1998b; Thompson *et al.*, 1998a

Solvents

Aitchison *et al.*, 2000; Burken, 2001; Chappell, 1997; Dietz and Schnoor, 2001; Gordon *et al.*, 1998;
Landmeyer, 2001; Lee *et al.*, 2000; Newman *et al.*, 1999, 1997

Petroleum Hydrocarbons/Radionuclides

Gommers *et al.*, 2000; Landmeyer, 2001; Zalesny *et al.*, 2005b

(poplars) and *Salix* (willows) exhibit fast growth (Dickmann and Stuart, 1983), elevated water usage (Hall *et al.*, 1998; Vose *et al.*, 2000), and extensive root systems (McLinn, Vondracek, and Aitchison, 2001). These traits are favorable for phytoremediation due to the need for quick plot establishment, hydraulic control, and filtering capabilities to reduce subsurface movement of the contaminants (Ferro *et al.*, 2001; Perttu and Kowalik, 1997). Landfill leachate contains organics and inorganics in need of remediation. Therefore, due to the increasing number of closed municipal landfills throughout North America, there is a growing need for cost-effective systems for on site leachate treatment (Zalesny *et al.*, 2007a). Pure species and hybrids (intra- and inter-specific) of *Populus* and *Salix* have been used to remediate a variety of ground contaminants (Table 1), of which many have been found in landfill leachate.

Boye (2002) irrigated *Salix viminalis* L. '78183' (osier willow) with landfill leachate and reported significant concentrations of copper, lead, and zinc in the shoots and roots. Erdman and Christenson (2000) tested the concentration of numerous elements found in the leaves of *Populus deltoides* Bartr. ex Marsh (eastern cottonwood) grown in soils contaminated with landfill leachate. Elevated levels of boron in the leaves indicated areas of soil contamination, while concentrations of elements such as zinc and sodium also were substantial in the tissues. Zalesny *et al.* (2006) irrigated a *Populus* F₁ hybrid between *P. nigra* L. (European black poplar) and *P. maximowiczii* A. Henry (Japanese poplar) 'NM6' with landfill leachate and reported a mean sapflow of 136 kg water tree⁻¹ d⁻¹ for 4-yr-old trees.

The success of such systems has prompted further use of leachate as a combination of irrigation and fertilization for the trees (Erdman and Christenson, 2000). A common protocol for such efforts has been to utilize a limited number of readily-available genotypes with decades of deployment in other applications, such as fiber or windbreaks. However, it

may be possible to increase phytoremediation success with proper genotypic screening and selection, followed by the field establishment of clones that exhibited favorable potential for clean-up of specific contaminants (Zalesny *et al.*, 2007a). We assert that there is an overwhelming need for testing and subsequent deployment of a variety of *Populus* and *Salix* genotypes, given current availability of clonal material (*i.e.*, >100,000 *Populus* offspring have been produced in the North Central United States in the last 50 years, and several hundred of those have made it to the clonal level of testing) (R.B. Hall, Iowa State University, personal communication) and the inherent genetic variation among and within these genera (Aravanopoulos, Kim, and Zsuffa, 1999; Rajora and Zsuffa, 1990).

This review consists of revising and combining common crop- and tree-improvement protocols to meet the objective of utilizing superior *Populus* and *Salix* clones for landfill covers. Such information is lacking for environmental clean-up technologies. However, centuries of plant-selection success in agronomy, horticulture, and forestry validate the need for similar approaches in phytoremediation. We have attempted to bridge the gap between these disciplines by describing project development, clone selection, tree establishment, and evaluation of success metrics in the context of their importance to utilizing trees for landfill covers, with emphasis on using leachate for irrigation.

PROJECT DEVELOPMENT

Identify Objectives, Biological Processes of Remediation, and Plant Traits of Interest

The first component of all phytoremediation systems is to identify the overall objectives of the project. Objectives vary with site characteristics, contaminant properties, and choice of plant species. In addition, it is important to identify the biological processes necessary for successful phytoremediation (Cunningham and Ow, 1996; Schnoor *et al.*, 1995), because those processes dictate the plant traits that should be evaluated. Parallel consideration of the processes and traits will help researchers and resource managers develop sound, realistic management objectives. Overall, given a lack of infinite resources, it is important to match the project objective to easily-measurable traits of interest that contribute to meaningful interpretations of phytoremediation success. Below we have provided a detailed summary of allometric, physiological, and anatomical traits that contribute to such success.

Two components of all systems assessing the uptake of organics and inorganics are whether the trees: 1) accumulate the contaminant at dangerous levels for tree survival and/or at concentrations that are toxic to fauna and 2) clean up the soil effectively (S.A. Rock, US EPA, personal communication). For example, phytoextraction is needed to extract and capture heavy metals (Angle and Linacre, 2005; Landberg and Greger, 1996). In contrast, root exudates contribute to rhizodegradation, the breakdown of organics in the rhizosphere (Burken and Schnoor, 1996; Jordahl *et al.*, 1997).

Phytostabilization occurs when contaminants are confined in the rhizosphere (Anderson, Guthrie, and Walton, 1993; Schnoor, 2000). Metabolic processes within the tree contribute to the degradation of organics in tree tissues, known as phytodegradation (Burken and Schnoor, 1997; Newman *et al.*, 1997). A process involved in the breakdown of inorganics and organics includes phytovolatilization, whereby the contaminant is extracted from the medium, metabolized, and transpired into the atmosphere (Newman *et al.*, 1997; Thompson, Ramer, and Schnoor, 1998b).

CLONE SELECTION

Identify and Select Favorable Clones from Phyto-recurrent Selection Cycles

A complete cycle of recurrent selection in plant breeding involves intermating individuals to develop progenies, evaluating the progenies for traits of interest, selecting favorable genotypes, and intermating the favorable genotypes (Figure 1). The primary objectives of recurrent selection are to: 1) increase the frequency of favorable alleles and, therefore, improve the mean of the new population and 2) retain the genetic variation of the original population as new progeny are developed (Hallauer and Miranda, 1988). Given that genetic gain is proportional to variation, breeders of *Populus* and *Salix* are fortunate because these genera exhibit extensive genetic variation relative to most other plant species (Eckenwalder, 1996). Heterosis, *i.e.*, hybrid vigor, is common in F_1 hybrids of *Populus* and *Salix* (Heilman, Ekuan, and Fogle, 1994), whereby the offspring are superior to either or both of the parents for the traits of interest. Selection within pure species or hybrids of *Populus* and *Salix* has the potential for increasing the success of using these genera for landfill covers.

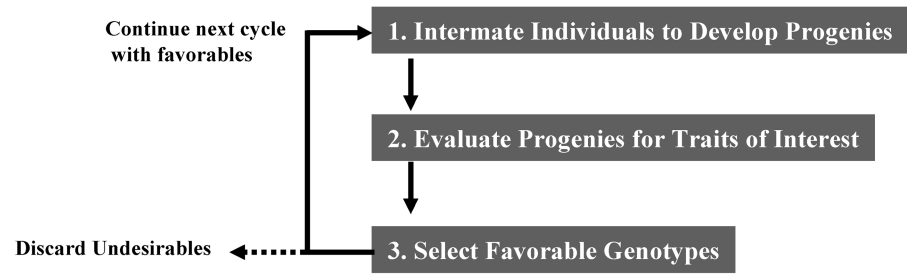
Similar to traditional recurrent selection, a complete cycle of phyto-recurrent selection using *Populus* and *Salix*, or any other vegetatively-propagated plant species with phytoremediation potential, involves selecting clones to be tested; evaluating the clones when irrigated with leachate; selecting favorable clones based on allometric, physiological, and anatomical traits of interest (see below); and evaluating the favorable clones (Figure 1). The primary objectives of phyto-recurrent selection are to choose clones for field deployment that have: 1) improved phytoremediation potential and 2) adequate genetic variation to guard against insect/disease outbreaks, unforeseen soil conditions (*e.g.*, drought/flood), and unfavorable genotype $\times$ environment interactions. To accomplish these objectives, it is important for researchers or resource managers to initially select clones that are either adapted to or have been successfully grown in local environments. *Populus* and *Salix* clones we have tested for phytoremediation purposes are listed in Table 2. Ideally, it is helpful to assess additional traits of interest during each cycle, with precision and complexity increasing as the number of clones tested decreases. Thus, these methods offer an opportunity for researchers to collect greater levels of information prior to field deployment. Likewise, the researcher or resource manager must balance precision with scope of inference, so that interpretations are meaningful yet can be applied to more than a limited number of experimental groups. Multiplicative, weighted-summation, and rank-summation selection indices that are efficient and easy to develop should be used to evaluate metrics during each cycle.

Zalesny *et al.* (2007a) reported successful use of phyto-recurrent selection when testing *Populus* genotypes representing five genomic groups. After irrigating with landfill leachate for three *ex situ* phyto-recurrent selection cycles lasting a total of 6 mo, eight superior *Populus* clones were selected from 25 original genotypes for the fourth cycle, a completed *in situ* study that was conducted for two growing seasons at the Oneida County Landfill in Rhinelander, WI, USA (45.6°N, 89.4°W). The long-term objectives of this system were to: 1) select superior clones that can be established on a larger scale and 2) continually irrigate the selected genotypes with leachate from the landfill, as a means of on-site treatment (J.A. Zalesny, Iowa State University, personal communication).

Recurrent Selection in Plant Breeding

Primary Objectives

- 1. Increase frequency of favorable alleles & improve mean of new population
- 2. Retain genetic variation of original population



Phyto-Recurrent Selection in Phytoremediation

Primary Objectives

Choose clones for field deployment that have:

- 1. Improved phytoremediation potential over original set of clones
- 2. Adequate genetic variation to guard against insect/disease outbreaks, changes in soil conditions (e.g. flood/drought), & unfavorable genotype × environment interactions

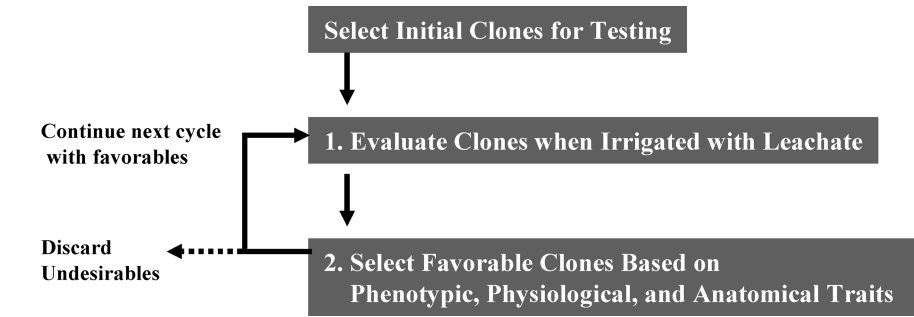


Figure 1 Comparison of recurrent selection used in plant breeding with phyto-recurrent selection used in phytoremediation. The overall goal of both methods is to select superior genotypes based on specific project objectives.

Once favorable clones are selected for deployment, establishment in the field is similar to that of agronomic crops. Proper intensive management includes consideration of: site requirements, cutting collection, site preparation, planting, and site maintenance.

Table 2 Genomic groups and clones of *Populus* and *Salix* tested by the authors for various phytoremediation needs

Genomic group	Cutting type	Clone
<i>Populus</i>		
(<i>P. trichocarpa</i> × <i>P. deltoides</i>) × <i>P. deltoides</i>	Unrooted	NC13377, NC13451, NC13460, NC13466, NC13475, NC13548, NC13552, NC13570, NC13608 NC13624, NC13649, NC13652, NC13661, NC13668, NC13670, NC13672, NC13680, NC13807, NC13850, NC13857, NC13863, NC13992, NC13999, NC14002, NC14018 80X00601, 80X01107, ISU25-4, ISU25-12, ISU25-21, ISU25-35, ISU25-R2, ISU25-R4, ISU25-R5 80X00601
<i>P. deltoides</i> × <i>P. deltoides</i> (F ₁ hybrid)	Rooted	119.16
"	Unrooted	
<i>P. deltoides</i> × <i>P. deltoides</i> (F ₂ hybrid)	Unrooted	
<i>P. deltoides</i> × <i>P. maximowiczii</i>	Rooted	Belgian25
"	Unrooted	313.23, 313.55, DM101, DM109, DM113, DM114, DM115, DM121, NC14104, NC14105, NC14106, NC14107
<i>P. nigra</i> × <i>P. maximowiczii</i>	Rooted	NM2
"	Unrooted	NM2, NM6
<i>P. deltoides</i> × <i>P. nigra</i>	Rooted	Eugenei (a.k.a. 'DN34'), I45-51
"	Unrooted	DN5, DN17, DN34 (a.k.a. 'Eugenei'), DN182, I45-51
<i>P. deltoides</i>	Rooted	252-4, 42-7
"	Unrooted	7300501, 8000105, 91.05.02, D121, D123, D124, D125
<i>Salix</i>		
<i>S. purpurea</i>	Unrooted	94003, 94012, FC185, FC189, FC190, PUR12
<i>S. eriocephala</i>	Unrooted	S25, S287
<i>S. eriocephala</i> 28 × <i>S. eriocephala</i> 24	Unrooted	S566
<i>S. interior</i> × <i>S. eriocephala</i>	Unrooted	S301
<i>S. discolor</i>	Unrooted	S365
<i>S. × dasyclados</i>	Unrooted	SV1
<i>S. sachalinensis</i>	Unrooted	SX61
<i>S. miyabeana</i>	Unrooted	SX67

Note: Authorities for the aforementioned species of *Populus* and *Salix* are as follows: *P. deltoides* Bartr. ex Marsh; *P. trichocarpa* Torr. & Gray; *P. nigra* L., *P. maximowiczii* A. Henry; *S. purpurea* L.; *S. eriocephala* Michx.; *S. interior* Rowlee.; *S. discolor* Mühl.; *S. sachalinensis* F. Schmidt; *S. miyabeana* Seemen.

TREE ESTABLISHMENT IN THE FIELD

Site Requirements

Soil depth, fertility, pH, and moisture/aeration must be considered when using *Populus* and *Salix* for phytoremediation of landfills and similarly-contaminated sites (Baker and Broadfoot, 1979; Schreiner, 1959). *Populus* genotypes grow best on deep, medium-textured soils where root penetration to a depth of at least 1 m is not interrupted by bedrock, the water table, hardpans, or gravel layers. The soils should be augmented with appropriate fertilizers, some of which may come from the leachate irrigation. Optimum pH is 5.0 to 7.5, with liming necessary on acid soils. *Populus* genotypes grow well on up- and bottom-land sites, provided the soils are well-drained. *Salix* requirements are similar to those of *Populus*. *Salix* genotypes require 0.5 m or greater soil depth, medium-textured loamy soils, pH ranging from 5.5 to 8.0, and imperfectly-drained to well-drained soils (Abrahamson *et al.*, 2002). *Populus* and *Salix* can withstand short-term flooding (Zalesny *et al.*, 2005b).

Cutting Collection

Populus and *Salix* propagules are either dormant, unrooted hardwood cuttings typically ranging in size from 15 to 45 cm in length and 1 to 2 cm in diameter (Abrahamson *et al.*, 2002; Stanturf *et al.*, 2001), rooted stock with four to seven major lateral roots and varying lengths of residual stems, or rooted cuttings reared in a greenhouse or growth chamber. Either type of rooted cuttings is preferred for genomic groups that have exhibited erratic rooting, such as *P. deltoides*. *Populus* whips up to about 3 m in length also have been used for phytoremediation systems, where there was a need to plant deep so that the tree roots intercept a soluble subsurface plume, to achieve greater biomass more rapidly, or to gain height quickly in periodically-flooded areas (Licht and Isebrands, 2005; Zalesny *et al.*, 2005b).

Cuttings are harvested from 1-yr-old shoots on stool beds grown in cutting orchards. A stool is a stump from which new shoots emerge. Each year the stool shoots are cut back to a height of 5 to 15 cm to allow the remaining buds to form new sprouts. Generally, cuttings are harvested between late December and mid March. However, *Populus* genomic influence is time-dependent for the collection of cuttings, with root development and tree growth being dependent upon date of shoot collection, given physiological responses associated with dormancy induction (Zalesny and Wiese, 2006). The health of the cutting material is critical to proper tree development. Cuttings must be disease-free, of the proper dimensions, and have well-developed vegetative buds. After collection, cuttings should be sealed and stored in plastic bags at approximately 5 °C. Premature shoot development prior to planting decreases survival in the field; therefore, such cuttings should not be planted (Abrahamson *et al.*, 2002). Some clones, particularly those of pure *P. deltoides* parentage, may not root fast enough to work well with the field planting of unrooted cuttings. For those clones, propagating rooted cuttings in a greenhouse, growth chamber, or nursery can be used to produce much more reliable planting stock. Such stock needs to be hardened off prior to planting on the remediation site by reducing day length, temperature, and moisture availability at the end of the production cycle.

Site Preparation

Proper site preparation is essential for the successful establishment of *Populus* and *Salix*, regardless of the system objectives. Inadequate site preparation drastically reduces survival and growth of these genera (Abrahamson *et al.*, 2002; Stanturf *et al.*, 2001). Therefore, it is important to have the commitment and resources in place for providing intensive culture techniques in growing the trees until canopy closure, which generally is 3 to 4 yr for *Populus* and 2 to 3 yr for *Salix*, depending on spacing (Bauer, 1996; Abrahamson *et al.*, 2002; Stanturf *et al.*, 2001). Care of *Populus* and *Salix* is similar to that of many agronomic crops, where mechanical treatment, chemical treatment, or a combination of both is used to remove most or all of the competing vegetation (Wiese *et al.*, 2006). Stanturf *et al.* (2001) and Abrahamson *et al.* (2002) provided information about specific chemicals for *Populus* and *Salix*, respectively.

A general site preparation timeline for *Populus* and *Salix* follows. In the year before planting (year 0), mow the existing vegetation during July, apply a combination of chemicals such as glyphosate and 2–4D to kill regrowth of grasses and weeds during August, and plow or deep-till with a rotary tiller to a depth of 25 cm followed by cross-disking during September. Plant a cover crop such as winter rye on sites with erosion problems during

September or October (Abrahamson *et al.*, 2002). Repeated applications of glyphosate may be necessary on sites with heavy grass competition. Chemical application on adjacent riparian areas should be treated with the aquatic-labeled glyphosate. Prior to planting (year 1), the site should be deep-tilled using a chisel plow or rotary tiller to ensure a deep, loose, and aerated soil. If the site had a cover crop of winter rye or regrowth of grasses, then it may be necessary to apply glyphosate prior to tilling.

For sites greater than 5 ha, mechanical preparation using a large tractor and chisel plow followed by disking (larger equipment to reduce time and expense) will yield a deep, loose soil that is ideal for root development. For sites less than 5 ha, a small tractor with a rotary tiller will provide deep tillage that provides a loose, aerated soil. In addition, for areas such as the North Central United States where white-tailed deer (*Odocoileus virginianus* Douglas) are a problem, we recommend the installation of deer fencing to prevent damage or mortality of the trees. A woven-wire fence, 2.4 m in height, is recommended for long-term fencing. Less expensive fencing can be installed using extruded plastic fabric that is lightweight, durable, almost invisible, and convenient to install for short-term use. Electric fencing is another alternative. Depending on the site, protection of the stems from girdling by small mammals also may be necessary.

Planting

Planting designs require careful consideration of a number of factors, including but not limited to: erosion prevention (*i.e.*, plant parallel to the contour of the land), tree spacing to provide optimum water uptake, and closer spacing for faster canopy closure. Eventually, closer spacing will lead to crowding and reduced growth, which can be prevented with a tree-removal plan according to the prescribed tree spacing listed below.

Populus genotypes should be planted when nighttime soil temperatures at a depth of 20 to 25 cm are at least 14 °C for four consecutive days (Zalesny *et al.*, 2005c). *Salix* genotypes grow best with warm temperatures and moist soils (Abrahamson *et al.*, 2002). Prior to planting, cuttings should be soaked upright (buds pointing upward) in water to 2/3 of the cutting height for about 3 d, or until root nodule formation is noticeable. Soaked cuttings should be stored in a cool, shady location and kept moist during planting.

Tree spacing for *Populus* and *Salix* depends upon site and cutting availability, along with consideration of the feasibility for proper vegetation management. Also, remediation objectives dictate spacing. However, in general, tree spacing for *Populus* varies from 2.1 × 3.0 m to 4.0 × 4.0 m, depending on the species and desired product (Stanturf *et al.*, 2001). Spacing for biomass production with *Salix* is a double-row system with 1.5 m between double-rows, 0.78 m between rows, and 0.6 m between plants within rows (Abrahamson *et al.*, 2002). For most phytoremediation plantings, we recommend 2.4 m between rows to allow for mechanical vegetation control using a small tractor with a tiller or disk. A pre-emergent herbicide such as oxyfluorene should be applied immediately following planting (when all vegetative buds are dormant), which will provide weed control for most of the first year.

Different planting devices must be used to accommodate varying cutting lengths. The smaller, unrooted cuttings require quick planting using a device called a dibble bar (straight rod, 2 cm in diameter, with a T handle) to punch a 20- to 25-cm hole, or a tree planter on a tractor if the site is fairly level. For rooted cuttings or extra long material (*i.e.*, 1.2 to 3.0-m whips), individual drilling to the desired depth using a power auger is necessary. Such deep-planted whips require special treatment such as warm air tubes to the

full length of belowground material to induce rooting (Licht and Isebrands, 2005). Overall, the researcher or resource manager must balance the costs associated with cutting material, along with handling and planting costs, with expected survival rates, based on the desired stocking rate (Zalesny *et al.*, 2005b).

Site Maintenance

It is important to keep the area between and within rows free of weed competition. Thus, chemical treatment, mechanical treatment, or some combination is necessary (see above). *Salix* genotypes are sensitive to post-emergent herbicides; therefore, either mechanical control or shielding of the trees is necessary for contact herbicide application if the pre-emergence herbicide cap fails (Abrahamson *et al.*, 2002). Tilling within and across rows with a rotary tiller is effective if the trees are planted at 2.4- × 2.4-m spacing, assuming the contour of the site allows use of a tractor. If dry conditions persist following planting, it will be necessary to provide supplemental water and/or leachate for several growing seasons or until the roots grow to a depth where they can capture ground water. We recommend installation of an irrigation system to supply supplemental water and leachate.

Also, it is important to monitor disease and insect damage to the trees, especially when such impacts may cause greater than 25% growth reduction (Coyle *et al.*, 2006). For example, heavy infestations of insects [*e.g.*, morning cloak butterfly, *Nymphalis antiopa* L. (Lepidoptera: Nymphalidae)] can defoliate entire trees in a short time. Primary insect and pathogen parameters include but are not limited to insect pests, leaf diseases, and stem diseases (Mattson *et al.*, 2001; Ostry *et al.*, 1988).

Additional types of monitoring are weather stations using inexpensive dataloggers for ambient and soil temperatures (Zalesny *et al.*, 2007b); rain gauges; tensiometers (soil moisture measurement); and occasional surveys of the planting to check for insects, diseases, and plant health.

EVALUATING METRICS OF SUCCESS

Non-Plant Related Variables

Soil testing before and after leachate treatment is one of the most important metrics of success for any landfill-cover phytoremediation system. Testing the contaminant levels in the irrigation leachate and irrigation water, where applicable, is equally-necessary. The combination of these data is important because such soil and irrigation concentrations provide a means of estimating the nutrient availability (Marschner, 1995), which is the first step in gauging potential concentrations of nutrient uptake and translocation, along with potential tree productivity (Ericsson, Rytter, and Linner, 1992). Other soil characteristics that are helpful include pH, texture, slope, history of use, organic matter content, base saturation, cation exchange capacity, and electroconductivity. In addition, the presence of certain soil fauna is important because such information provides a means of estimating overall soil health under conditions of leachate irrigation.

Allometric Traits

Allometric traits for landfill-cover systems are meaningful, despite being measured easily. Often, such traits are matched to specific biological processes of remediation.

For example, the extensiveness of a genotype's root system is crucial for the success of rhizodegradation and phytostabilization (Anderson *et al.*, 1993). The most common allometric traits evaluated when using *Populus* and *Salix* for phytoremediation and other applications include, but are not limited to, height, diameter, biomass, leaf area, leaf number, root area, root length, and number of roots. The main drawback of such traits is that they do not provide information about specific phytoremediation success. However, such metrics are useful for evaluating the level of tree establishment and health, along with becoming an *in situ* component of a phytorecurrent selection cycle. That is, trees that fail to establish cannot be considered for further deployment and are eliminated from the sample of favorable clones (Zalesny *et al.*, 2007a).

In addition, allometric traits provide an inexpensive and efficient means of evaluating the potential of the genotypes, especially when tested with well-developed experimental designs and requisite precision levels. The long history of designs that support estimation of genetic data such as repeatabilities (*i.e.*, heritabilities in crop and tree improvement) and correlations (*i.e.*, genetic, phenotypic, and environmental) support recommendations of using generalist genotypes that perform well over broad geographic areas (low phenotypic plasticity) or specialist genotypes that perform well in designated breeding/production zones (high phenotypic plasticity) (Dickmann and Keathley, 1996; Orlovic *et al.*, 1998; Zalesny, Riemenschneider, and Hall, 2005a). Such quantitative genetic data are acquired from physiological and anatomical traits, as well.

Physiological and Anatomical Traits

Physiological and anatomical traits are those that cannot be measured easily because the data result from processes and developmental stages that occur within the plants. As with allometric traits, however, physiological and anatomical traits are matched to specific biological processes of remediation. For example, the level of a genotype's stomatal conductance is crucial for the success of phytovolatilization (Vose *et al.*, 2000). The most common physiological and anatomical traits evaluated when using *Populus* and *Salix* for phytoremediation and other applications include, but are not limited to, contaminant concentrations in the roots, stems, and leaves; sapflow/water usage; stomatal conductance; number of stomata per leaf; and presence of root exudates. The main drawback of such traits is that testing is laborious and expensive. However, such metrics are necessary for evaluating specific levels of phytoremediation success.

CONCLUSIONS AND PRACTICAL IMPLICATIONS

Short rotation woody crops have been used for phytoremediation of a variety of contaminants (Table 1). *Populus* and *Salix* genotypes exhibit traits that are needed for landfill covers with trees. Researchers have reported successful tree growth and remediation potential when these genera have been irrigated with landfill leachate (Boye, 2002; Erdman and Christenson, 2000; Zalesny *et al.*, 2006). The current availability of clonal material representing broad genetic variation provides a means for testing and subsequent deployment of *Populus* and *Salix* genotypes that have greater potential for positive responses to landfill leachate irrigation than most clones that have been utilized for this purpose.

Combining information from crop and tree improvement methods used in agronomy, horticulture, and forestry with pre-existing environmental clean-up technologies may enhance the success of landfill cover systems. We assert attention to project development,

clone selection, tree establishment, and evaluation of success metrics will help bridge the gap between these related fields. The system begins with decisions on project objectives and matching biological processes of remediation with plant traits. Next, it is important to evaluate, identify, and select favorable clones from phyto-recurrent selection cycles. Once favorable clones have been selected, tree establishment in the field is intensive, with necessary management similar to that used for agronomic species. Lastly, metrics of success should include a combination of non-plant related variables, along with allometric, physiological, and anatomical plant traits. Exclusion of any category substantially decreases the amount of information used to gauge the success of the phytoremediation system.

Overall, we believe this crop and tree improvement approach contributes to the potential for greater phytoremediation success when irrigating trees with landfill leachate. In addition, we hope these methodologies can help researchers and resource managers move closer to obtaining long-term (*i.e.*, rotation age) remediation data from landfill covers and other phytoremediation systems.

ACKNOWLEDGMENTS

We are grateful to Steven Rock (US EPA) for the opportunity to provide our ideas to others interested in advancing phytoremediation technologies, along with his insightful technical reviews and suggestions. We thank the following plant breeders who contributed meaningful critiques of the manuscript: Dr. Richard B. Hall (Iowa State University—*Populus* spp., *Alnus* spp.), Dr. A. Assibi Mahama (Iowa State University—*Glycine max*, *Populus* spp., *Sorghum bicolor*, *Zea mays*), and Mr. Bernard McMahon (University of Minnesota National Resources Research Institute —*Populus* spp.). Also, we appreciate review of earlier versions of the manuscript from Robert Bridges, Deahn Donner, Neil Nelson, Adam Wiese, and Jill Zalesny.

REFERENCES

- Abrahamson, L.P., Volk, T.A., Kopp, R.F., White, E.H., and Ballard, J.L. 2002. *Willow Biomass Producer's Handbook*. Syracuse, State University of New York, College of Environmental Science and Forestry, 31 pp.
- Aitchison, E.W., Kelley, S.L., Alvarez, P.J.J., and Schnoor, J.L. 2000. Phytoremediation of 1,4-Dioxane by hybrid poplar trees. *Water Environ. Res.* **72**, 313–321.
- Anderson, T.A., Guthrie, E.A., and Walton, B.T. 1993. Bioremediation in the rhizosphere. *Environ. Sci. Technol.* **27**, 2630–2636.
- Angle, J.S. and Linacre, N.A. 2005. Metal phytoextraction: A survey of potential risks. *Int. J. Phytoremed.* **7**, 241–254.
- Aravanopoulos, F.A., Kim, K.H., and Zsuffa, L. 1999. Genetic diversity of superior *Salix* clones selected for intensive forestry plantations. *Biomass Bioenergy* **16**, 249–255.
- Baker, J.B. and Broadfoot, W.M. 1979. A practical field method of site evaluation for commercially important southern hardwoods. General Technical Report SO-26, p. 51. New Orleans, LA, USDA Forest Service, Southern Research Station.
- Bañuelos, G.S., Shannon, M.C., Ajwa, H., Draper, J.H., Jordahl, J., and Licht, L. 1999. Phytoextraction and accumulation of boron and selenium by poplar (*Populus*) hybrid clones. *Int. J. Phytoremed.* **1**, 81–96.
- Bauer, E.O. 1996. Intensively cultured hybrid poplar: an investment in rural economic development: From hardwood cutting to harvest in 10–15 years. Informational Bulletin, St. Paul, MN, USDA Forest Service, North Central Forest Experiment Station, 6. pp.

- Boye, K. 2002. Phytoextraction of Cu, Pb and Zn: A greenhouse study. Report, Uppsala, Sweden, Swedish University of Agricultural Sciences. Department of Soil Sciences, 29 pp.
- Burken, J.G. 2001. Uptake and volatilization of chlorinated solvents by poplars at field-scale. In: *Phytoremediation, Wetlands, and Sediments*, pp. 113–120. (Leeson, A., Foote, E.A., Banks, M.K., and Magar, V.S., Eds.). Columbus, OH, Battelle.
- Burken, J.G. and Schnoor, J.L. 1996. Phytoremediation: Plant uptake of atrazine and role of root exudates. *J. Environ. Eng.* **122**, 958–963.
- Burken, J.G. and Schnoor, J.L. 1997. Uptake and metabolism of atrazine by poplar trees. *Environ. Sci. Technol.* **31**, 1399–1406.
- Burken, J.G. and Schnoor, J.L. 1998. Predictive relationships for uptake of organic contaminants by hybrid poplar trees. *Environ. Sci. Technol.* **32**, 3379–3385.
- Campbell, A.G., Zhang, X.G., and Tripepi, R.R. 1995. Composting and evaluating a pulp and paper sludge for use as a soil amendment/mulch. *Compost Sci. Utiliz.* **3**, 84–95.
- Chappell, J. 1997. Phytoremediation of TCE using *Populus*. Status report prepared for the United States Environmental Protection Agency Technology Innovation Office under a National Network of Environmental Management Studies Fellowship, 38 pp.
- Coyle, D.R., Coleman, M.D., Durant, J.A., and Newman, L.A. 2006. Multiple factors affect pest and pathogen damage on 31 *Populus* clones in South Carolina. *Biomass Bioenergy* **30**, 759–768.
- Cunningham, S.D. and Ow, D.W. 1996. Promises and prospects of phytoremediation. *Plant Physiol.* **110**, 715–719.
- Dickmann, D.I. and Keathley, D.E. 1996. Linking physiology, molecular genetics, and the *Populus* ideotype. In: *Biology of Populus and Its Implications for Management and Conservation*, Part II, ch. 19, pp. 491–514. (Stettler, R.F., Bradshaw, H.D., Jr., Heilman, P.E., and Hinckley, T.M., Eds.). Ottawa, ON, NRC Research Press, National Research Council of Canada.
- Dickmann, D.I. and Stuart, K.W. 1983. *The Culture of Poplars in Eastern North America*. East Lansing, Department of Forestry, Michigan State University, 168 pp.
- Dietz, A.C. and Schnoor, J.L. 2001. Phytotoxicity of chlorinated aliphatics to hybrid poplar (*Populus deltoides* × *nigra* DN34). *Environ. Toxicol. Chem.* **20**, 389–393.
- Eckenwalder, J.E. 1996. Systematics and evolution of *Populus*. In: *Biology of Populus and Its Implications for Management and Conservation*, Part I, ch. 1., pp. 7–32. (Stettler, R.F., Bradshaw, H.D., Jr., Heilman, P.E., and Hinckley, T.M., Eds.). Ottawa, ON, NRC Research Press, National Research Council of Canada.
- Erdman, J.A. and Christenson, S. 2000. Elements in cottonwood trees as an indicator of ground water contaminated by landfill leachate. *Ground Water Monitoring Remed.* **20**, 120–126.
- Ericsson, T., Rytter, L., and Linder, S. 1992. Nutritional dynamics and requirements of short rotation forests. In: *Ecophysiology of Short Rotation Forest Crops*, pp. 35–65. (Mitchell, C.P., Ford-Robertson, J.B., Hinckley, T., and Sennerby-Forsse, L., Eds.). London, Elsevier Applied Science.
- Eriksson, J. and Ledin, S. 1999. Changes in phytoavailability and concentration of cadmium in soil following long term *Salix* cropping. *Water, Air, Soil Pollut.* **114**, 171–184.
- Ferro, A., Chard, J., Kjellgren, R., Chard, B., Turner, D., and Montague, T. 2001. Groundwater capture using hybrid poplar trees: evaluation of a system in Ogden, Utah. *Int. J. Phytoremed.* **3**, 87–104.
- Gatliff, E.G. 1994. Vegetative remediation process offers advantages over traditional pump-and-treat technologies. *Remed.* **4**, 343–352.
- Glass, D.J. 1999. Current market trends in phytoremediation. *Int. J. Phytoremed.* **1**, 1–8.
- Gommers, A., Vandenove, H., Smolders, E., and Merckx, R. 2000. Screening willow clones for radiocesium uptake at varying potassium supply in solution culture. *Int. J. Phytoremed.* **2**, 243–253.
- Gordon, M., Choe, N., Duffy, J., Ekuan, G., Heilman, P., Muiznieks, I., Ruszaj, M., Shurtleff, B.B., Strand, S., Wilmouth, J., and Newman, L. 1998. Phytoremediation of trichloroethylene with hybrid poplars. *Environ. Health Perspectives* **106**, 1001–1004.

- Greger, M. and Landberg, T. 1999. Use of willow in phytoextraction. *Int. J. Phytoremed.* **1**, 115–123.
- Greger, M. and Landberg, T. 2001. Investigation on uptake of Cd, Cu, and Zn in *Salix viminalis* of different ages and rotations. In: *Salix Clones with Different Properties to Accumulate Heavy Metals for Production of Biomass*, pp. 6–18. (Greger, M., Landberg, T., and Berg, B., Eds.). Stockholm, Sweden, University of Stockholm.
- Hall, R.L., Allen, S.J., Rosier, P.T.W., and Hopkins, R. 1998. Transpiration from coppiced poplar and willow measured using sap-flow methods. *Agricultural Forest Meteorol.* **90**, 275–290.
- Hallauer, A.R. and Miranda, J.B. 1988. *Quantitative Genetics in Maize Breeding*. 2nd ed. Ames, Iowa State University Press, 468 pp.
- Hasselgren, K. 1998. Use of municipal waste products in energy forestry: Highlights from 15 years of experience. *Biomass Bioenergy* **15**, 71–74.
- Heilman, P.E., Ekuan, G., and Fogle, D.B. 1994. Above- and below-ground biomass and fine roots of 4-year-old hybrids of *Populus trichocarpa* × *Populus deltoides* and parental species in short-rotation culture. *Canadian J. Forest Res.* **24**, 1186–1192.
- Isebrands, J.G. and Karnosky, D.F. 2001. Environmental benefits of poplar culture. In: *Poplar Culture in North America*, Part A, ch. 6, pp. 207–218. (Dickmann, D.I., Isebrands, J.G., Eckenwalder, J.G., and Richardson, J., Eds.). Ottawa, ON, NRC Research Press, National Research Council of Canada.
- Jordahl, J.L., Foster, L., Schnoor, J.L., and Alvarez, P.J.J. 1997. Effect of hybrid poplar trees on microbial populations important to hazardous waste bioremediation. *Environ. Toxicol. Chem.* **16**, 1318–1321.
- Klang-Westin, E. and Eriksson, J. 2003. Potential of *Salix* as phytoextractor for Cd on moderately contaminated soils. *Plant Soil* **249**, 127–137.
- Labrecque, M., Teodorescu, T.I., and Daigle, S. 1998. Early performance and nutrition of two willow species in short-rotation intensive culture fertilized with wastewater sludge and impact on the soil characteristics. *Canadian J. Forest Res.* **28**, 1621–1635.
- Landberg, T. and Greger, M. 1994. Can heavy metal tolerant clones of *Salix* be used as vegetation filters on heavy metal contaminated land?. In: *Willow Vegetation Filters for Municipal Wastewaters and Sludges*, pp. 133–144. (Aronsson, P. and Perttu, K., Eds.). Uppsala, Sweden, Report 50 of the Swedish University of Agricultural Sciences.
- Landberg, T. and Greger, M. 1996. Differences in uptake and tolerance to heavy metals in *Salix* from unpolluted and polluted areas. *Appl. Geochem.* **11**, 175–180.
- Landmeyer, J.E. 2001. Monitoring the effect of poplar trees on petroleum-hydrocarbon and chlorinated-solvent contaminated ground water. *Int. J. Phytoremed.* **3**, 61–85.
- Lee, R.W., Jones, S.A., Kuniansky, E.L., Harvey, G., Lollar, B.S., and Slater, G.F. 2000. Phreatophyte influence on reductive dechlorination in a shallow aquifer contaminated with trichloroethene (TCE). *Int. J. Phytoremed.* **2**, 193–211.
- Licht, L.A. and Isebrands, J.G. 2005. Linking phytoremediated pollutant removal to biomass economic opportunities. *Biomass Bioenergy* **28**, 203–218.
- Luyssaert, S., Van Meirvenne, M., and Lust, N. 2001. Cadmium variability in leaves of *Salix fragilis*: Simulation and implications for leaf sampling. *Canadian J. Forest Res.* **31**, 313–321.
- Marschner, H. 1995. *Mineral Nutrition of Higher Plants*. 2nd ed. London, Academic, 889 pp.
- Mattson, W.J., Hart, E.A., Volney, W., and Jan, A. 2001. Insect pests of *Populus*: Coping with the inevitable. In: *Poplar Culture in North America*, Part A, ch. 7, pp. 219–248. (Dickmann, D.I., Isebrands, D.J.G., Eckenwalder, J.E., and Richardson, J., Eds.). Ottawa, ON, NRC Research Press, National Research Council of Canada.
- McLinn, E.L., Vondracek, J.E., and Aitchison, E.A. 2001. Monitoring remediation with trembling leaves: Assessing the effectiveness of a full-scale phytoremediation system. In: *Phytoremediation, Wetlands, and Sediments*, pp. 121–127. (Leeson, A., Foote, E.A., Banks, M.K., and Magar, V.S., Eds.). Columbus, OH, Battelle.

- Moffat, A.J., Armstrong, A.T., and Ockleston, J. 2001. The optimization of sewage sludge and effluent disposal on energy crops of short rotation hybrid poplar. *Biomass Bioenergy* **20**, 161–169.
- Newman, L.A., Strand, S.E., Choe, N., Duffy, J., Ekuan, G., Ruszaj, M., Shurtleff, B.B., Wilmoth, J., Heilman, P., and Gordon, M.P. 1997. Uptake and biotransformation of trichloroethylene by hybrid poplars. *Environ. Sci. Technol.* **31**, 1062–1067.
- Newman, L.A., Wang, X., Muiznieks, I.A., Ekuan, G., Ruszaj, M., Cortellucci, R., Domroes, D., Karscig, G., Newman, T., Crampton, R.S., Hashmonay, R.A., Yost, M.G., Heilman, P.E., Duffy, J., Gordon, M.P., and Strand, S.E. 1999. Remediation of trichloroethylene in an artificial aquifer with trees: A controlled field study. *Environ. Sci. Technol.* **33**, 2257–2265.
- O'Neill, G.J. and Gordon, A.M. 1994. The nitrogen filtering capability of Carolina poplar in an artificial riparian zone. *J. Environ. Quality* **23**, 1218–1223.
- Orlovic, S., Guzina, V., Krstic, B., and Merkulov, L. 1998. Genetic variability in anatomical, physiological and growth characteristics of hybrid poplar [*Populus × euramericana* Dode (Guinier)] and eastern cottonwood (*Populus deltoides* Bartr.) clones. *Silvae Genetica* **47**, 183–190.
- Ostry, M.E., Wilson, L.F., McNabb, H.S., Jr., and Moore, L.M. 1988. *A Guide to Insect, Disease, and Animal Pests of Poplars*. Washington, DC, USDA Agriculture Handbook 677, 118 pp.
- Perttu, K.L. 1993. Biomass production and nutrient removal from municipal wastes using willow vegetation filters. *J. Sustainable Forestry* **1**, 57–70.
- Perttu, K.L. and Kowalik, P.J. 1997. *Salix* vegetation filters for purification of water and soils. *Biomass Bioenergy* **12**, 9–19.
- Punshon, T. and Dickinson, N.M. 1997. Acclimation of *Salix* to metal stress. *New Phytologist* **137**, 303–314.
- Rajora, O.P. and Zsuffa, L. 1990. Allozyme divergence and evolutionary relationships among *Populus deltoides*, *P. nigra*, and *P. maximowiczii*. *Genome* **33**, 44–49.
- Roygard, J.K.F., Clothier, B.E., Green, S.R., and Bolan, N.S. 2001. Tree species for recovering nitrogen from dairy-farm effluent in New Zealand. *J. Environ. Quality* **30**, 1064–1070.
- Sander, M. and Ericsson, T. 1998. Vertical distribution of plant nutrients and heavy metals in *Salix viminalis* stems and their implications for sampling. *Biomass Bioenergy* **14**, 57–66.
- Schnoor, J.L. 2000. Phytostabilization of metals using hybrid poplar trees. In: *Phytoremediation of Toxic Metals: Using Plants to Clean Up the Environment*, ch. 9, pp. 133–150. (Raskin, I. and Ensley, B.D., Eds.). New York, John Wiley.
- Schnoor, J.L., Licht, L.A., McCutcheon, S.C., Wolfe, N.L., and Carreira, L.H. 1995. Phytoremediation of organic and nutrient contaminants. *Environ. Sci. Technol.* **29**, 318–323A.
- Schreiner, E.J. 1959. Production of poplar timber in Europe and its significance and application in the United States. Agriculture Handbook No. 150, pp. 124. Washington, DC, USDA Forest Service.
- Sealock, G.A. 2002. Phytoremediation of explosives using *Populus deltoides*. MS Thesis. Athens, Univ. of Georgia, 70 pp.
- Stanturf, J.A., van Oosten, C., Netzer, D.A., Coleman, M.D., and Portwood, C.J. 2001. Ecology and silviculture of poplar plantations. In: *Poplar Culture in North America*, Part A, ch. 5, pp. 153–206. (Dickmann, D.I., Isebrands, J.G., Eckenwalder, J.E., and Richardson, J., Eds.). Ottawa, ON, NRC Research Press, National Research Council of Canada.
- Thompson, P.L., Ramer, L.A., Guffey, A.P., and Schnoor, J.L. 1998a. Decreased transpiration in poplar trees exposed to 2,4,6-trinitrotoluene. *Environ. Toxicol. Chem.* **17**, 902–906.
- Thompson, P.L., Ramer, L.A., and Schnoor, J.L. 1998b. Uptake and transformation of TNT by hybrid poplar trees. *Environ. Sci. Technol.* **32**, 975–980.
- Vose, J.M., Swank, W.T., Harvey, G.J., Clinton, B.D., and Sobek, C. 2000. Leaf water relations and sapflow in eastern cottonwood (*Populus deltoides* Bartr.) trees planted for phytoremediation of a groundwater pollutant. *Int. J. Phytoremed.* **2**, 53–73.

- Wiese, A.H., Netzer, D.A., Riemenschneider, D.E., and Zalesny, R.S. Jr. 2006. A weed compaction roller system for use with mechanical herbicide application. *Northern J. Appl. Forestry* **23**, 66–69.
- Wong, M.H. and Leung, C.K. 1989. Landfill leachate as irrigation water for tree and vegetable crops. *Waste Management Res.* **7**, 311–324.
- Zalesny, R.S., Jr., Riemenschneider, D.E., and Hall, R.B. 2005a. Early rooting of dormant hardwood cuttings of *Populus*: analysis of quantitative genetics and genotype × environment interactions. *Canadian J. Forest Research* **35**, 918–929.
- Zalesny, R.S., Jr., Bauer, E.O., Hall, R.B., Zalesny, J.A., Kunzman, J., Rog, C.J., and Riemenschneider, D.E. 2005b. Clonal variation in survival and growth of hybrid poplar and willow in an *in situ* trial on soils heavily contaminated with petroleum hydrocarbons. *Int. J. Phytoremed.* **7**, 177–197.
- Zalesny, R.S., Jr., Hall, R. B., Bauer, E.O., and Riemenschneider, D.E. 2005c. Soil temperature and precipitation affect the rooting ability of dormant hardwood cuttings of *Populus*. *Silvae Genetica* **54**, 47–58.
- Zalesny, R.S., Jr. and Wiese, A.H. 2006. Date of shoot collection, genotype, and original shoot position affect early rooting of dormant hardwood cuttings of *Populus*. *Silvae Genetica* **55**, 169–182.
- Zalesny, R.S., Jr., Wiese, A.H., Bauer, E.O., and Riemenschneider, D.E. 2006. Sapflow of hybrid poplar (*Populus nigra* L. × *P. maximowiczii* A. Henry ‘NM6’) during phytoremediation of landfill leachate. *Biomass Bioenergy* **30**, 784–793.
- Zalesny, R.S., Jr. and Bauer, E.O. 2007. Evaluation of *Populus* and *Salix* continuously irrigated with landfill leachate. II. Soils and early tree development. *Int. J. Phytoremed.* **9**, 307–323.
- Zalesny, J.A., Zalesny, R.S., Jr., Wiese, A.H., and Hall, R.B. 2007a. Choosing tree genotypes for phytoremediation of landfill leachate using phyto-recurrent selection. *Int. J. Phytoremed.*, in press.
- Zalesny, R.S., Jr., Wiese A. H., Bauer, E.O., Headlee, W.L., Hall, R.B., Mahama, A.A., and Zalesny, J.A. 2007b. An inexpensive and reliable monitoring station design for use with lightweight, compact data loggers. *Tree Planters’ Notes* **52**, 32–35.