Phytoremediation of Dissolved Phase Organic Compounds: Optimal Site Considerations Relative to Field Case Studies

Harry R. Compton

George R. Prince

Scott C. Fredericks

Christopher D. Gussman

The United States Environmental Protection Agency/Environmental Response Team (EPA/ERT) has been supporting and implementing the use of phytoremediation to remediate dissolved phase organic compounds at Superfund sites since March 1996. Since then, ERT has applied phytoremediation field plots, both pilot and full scale, to a variety of field conditions. These active sites vary considerably as to depth to groundwater, groundwater transmissivity, contaminant concentrations, contaminant hydrophobicity, climate, planting design, plant selection, planting technique, and type of monitoring. Here we compare the literature and discuss lessons learned at five Superfund sites. Current maintenance and monitoring techniques at these sites are also discussed with recommendations for the maintenance and monitoring of similar sites in the future. © 2003 Wiley Periodicals, Inc.

INTRODUCTION

Phytoremediation is the use of living plants for in-situ remediation of contaminated soil, sludges, sediments, and groundwater primarily through degradation, removal, or containment. More specifically, the term phytoremediation or phytotechnology encompasses application of plants for hydraulic control, degradation, sorption, translocation, transpiration, and rhizosphere-enhanced degradation of contaminants. The term also captures vegetative landfill caps, constructed treatment wetlands, and the restoration/revegetation of damaged mine lands (EPA, 1998). This technique can be used for the remediation of inorganic contaminants as well as organic contaminants. In this article we focus primarily on the application of woody plants to hydraulically contain and degrade soluble organic compounds in the groundwater. The cost effectiveness of phytoremediation has been touted as the primary advantage of this innovative technology since it emerged in the mid-1990s. But the advantages have been found to go well beyond cost savings based on experiences under various cleanup programs, especially the Superfund program.

PHYTOREMEDIATION AND THE SUPERFUND PROGRAM

The discussion below is based on the authors' experience derived from directing projects within the Superfund program. Most projects have shown promising results. In general, phytoremediation is viewed under Superfund as follows:

- It is not a panacea—it has concerns and limitations;
- It is attractive because it is cost-effective and publicly acceptable;

DOI: 10.1002/rem.10072

- It appears to have greater effectiveness at low to moderate concentrations, and often as part of a treatment train; and
- It can be a tool for both remediation and restoration.

Although this technology has been used as several Superfund sites successfully, the EPA Superfund Office has found a number of concerns and limitations. The remediation process can create attractive nuisances and food chain exposure, and take time for concentrations to reach regulatory levels. In addition, the EPA has recognized the need to use native plants and manage unwanted invasive plants. These were some of the key issues ERT considered when it implemented a comprehensive monitoring program at the five sites discussed in this article. The monitoring program required consistency, yet it needed to address site and contaminant-specific design concerns. It made sense to address remediation objectives and issues in monitoring plans. The impacts of temporal, microclimate changes, as a function of regional growing seasons and diurnal fluctuations on the parameters studied in the monitoring efforts were also considered.

Since the inception of the Superfund Program in 1981, thousands of sites have been actively remediated.

At all Superfund sites, one of the most important considerations for selecting a remedy is the eventual beneficial reuse of the property. Local community concerns are given priority in deciding what to do with a site following remediation. (This philosophy is embodied in the Superfund Revitalization Initiative.) Sometimes, the site can serve a valuable economic purpose; at other times, it can provide an important aesthetic function as a green use, such as a wildlife sanctuary or recreational area. Many sites are being used to create critical sensitive habitats, nature parks, wild bird sanctuaries, and similar green uses. To date over 60,000 acres are in use, or are soon to be in use, for ecological and recreational purposes.

Since the inception of the Superfund Program in 1981, thousands of sites have been actively remediated. Not all these sites have contaminated soils, but most do. Historically, soils were excavated and taken off-site to a treatment facility or landfill. Other remediation approaches were not likely considered. Recently, the trend is to remediate these soils on-site, if technically and economically feasible, with off-site disposal as a final option. Sites vary greatly from one another in all characteristics imaginable. Contaminants of concern vary greatly in quantity, type, and distribution. Yet, some chemicals, or classes of contaminants, are relatively more common and appear regularly at many sites. Dissolved phase organic compounds, such as trichloroethylene (TCE), represent a group of such contaminants.

Trichloroethylene—A Ubiquitous Contaminant

Trichloroethylene (TCE) and its family of short-chain halogenated hydrocarbons are omnipresent groundwater contaminants found at many Superfund sites. Given that approximately 100,000 tons of TCE alone are generated annually for degreasing and solvent use for fats, oils and waxes, it is inevitable that spills and releases occur. Trichloroethylene is physically a dense non-aqueous phase liquid (DNAPL), denser than water and therefore often found in undissolved pockets within the groundwater. Because of this, treatment is difficult by conventional techniques, such as pump and treat, where the pockets and sorbed fractions continually dissolve into the aqueous phase in groundwater over time. Many of the common chlorinated solvents are known or suspected carcinogens, and almost all can cause kidney and liver damage. Interestingly, many have a rather short half-life in the atmosphere, e.g., from five to six days for TCE.

Trichloroethylene may also be degraded in soil by microorganisms and this may be enhanced by the presence of a rhizosphere (Anderson & Walton, 1995).

Phytoremediation as a Tool

Phytoremediation technology has been implemented at several contaminated sites and has been the focus of many research experiments over the past ten years. The term phytoremediation has been used for several applications in which plants were used to treat different types of contaminants, including heavy metals, petroleum hydrocarbons, chlorinated solvents, radionuclides, pesticides, and even excess nutrients (EPA, 2000). The method of action for remediation varies, and includes direct metabolism or translocation of the contaminant(s) of interest by the plant as well as degradation by microorganisms associated with the plant rhizosphere. Although the definition of phytoremediation is somewhat broad, destruction, removal, or immobilization of the compounds of interest should be directly attributed to the plant species involved. A large diversity of phytoremediation technologies, proven or otherwise, is available to project managers, and techniques are constantly evolving in this emerging technology. Current technologies may be observed at http://www.clu-in.org.

Phytoremediation can only be effective, obviously, under conditions, which permit growth of the plant species of interest.

Despite its broad application, the use of phytoremediation has several conditional limitations, which may prevent or limit its use at many sites. Phytoremediation can only be effective, obviously, under conditions, which permit growth of the plant species of interest. The contaminants present at the site must first be identified and then evaluated to determine if they can be effectively remediated by phytoremediation. Mixed contaminants may cause problems in that only one of the compounds may be affected or their combination may cause difficulties in plant growth or soil structure. The plants or tree utilized must be able to contact the contaminant of interest, but the contaminant concentration must not be phytotoxic. The project manager or landowner must also have the luxury of time to implement phytoremediation, which may occur over the course of months to decades to be fully effective. Although the cost associated with phytoremediation is generally lower than conventional methods, personnel must be available to oversee and implement planting, maintenance (water, fertilizer, pest and weed control), and sometimes harvest and disposal of the plants. Cost is difficult to determine, as it will depend on local growing conditions and the necessity of maintenance and monitoring. Pilot-scale and field-scale tests to date are generally far more costly than would be predicted for passive remediation. There are, however, many sites where phytoremediation may be utilized, either as the sole cleanup source or in combination with other remedial technologies. Finally, should the groundwater contamination pose an immediate threat to human health or environment, a more aggressive technology, and not phytoremediation, must be employed.

The Lowly Hybrid Poplar Takes on an Important New Role

The hybrid poplar was never considered especially beautiful or desirable when considering the great variety of trees available. Its only saving grace was its ability to grow rapidly, and thus was used extensively as windbreakers. It was this attribute—the propensity for very rapid growth—that would dramatically change the role of the poplar. Within the past decade hybrid poplars have emerged as the tree of choice for phytoremediation of organic compounds.

The widespread use of hybrid poplars originated with the silviculture industry. More than 30 species of poplars encompass worldwide distribution. Different species can be found growing in varied habitats and locations. In addition, most poplar species seem to be inherently variable and different ecotypes can vary greatly in morphological and physiological characteristics. Besides the variability within species, cross-ability among many of the species is very high, allowing the creation of simple and complex hybrids. The use of hybrids potentially allows desirable traits from different species to be combined, and hybrids may also demonstrate heterosis (hybrid vigor), which surpasses the parent species in one or more measurable characteristics. Many of the poplar species and hybrids are also easy to propagate vegetatively; and desirable clones can be easily multiplied to create large, uniform stands through the use of cuttings. Large trees can be grown on cleared land in a relatively short period of time, and specific clones can be found which are adapted to many different soil and climate types.

When the idea to utilize a tree species to clean contaminated soil and groundwater came into being, hybrid poplars were the ideal choice for further testing. This is because small trees, or even non-rooted whips planted on a site, will quickly increase in biomass while utilizing local moisture and nutrients. The breakdown and/or translocation of contaminants are a desirable physiological side effect. Trees are also perennial and therefore do not need frequent replanting and have relatively large and deep root systems to reach contaminants. In fact, poplars are considered phreatophytic. That is, they are water-loving and their roots will seek out groundwater. A seasonal reversal in groundwater flow patterns has been observed on at least one of the USEPA/ERT sites. In nature, poplars are generally associated with sites that have abundant or continuous groundwater/moisture, such as along stream banks. Reciprocally, it would appear, by their preferred growing environment and measured stomatal conductance, that poplars transpire relatively large amounts of water. These characteristics are also beneficial in their application to phytoremediation, where greater use of groundwater translates to a greater probability of contact and uptake of contaminants, or even curtailing (or possibly reversing) lateral movement of groundwater and associated further spread of the contaminants of concern.

When the idea to utilize a tree species to clean contaminated soil and groundwater came into being, hybrid poplars were the ideal choice for further testing.

How Do They Do That?

Hybrid poplars have, in general, fulfilled their goals as the tree of choice for phytoremediation. Suitable hybrid clones grow rapidly on most sites provided their basic needs are met. Pot, lysimeter, and field studies have demonstrated uptake of organic contaminants such as TCE and have provided solid evidence of its breakdown within the plant tissue. Early groundbreaking work performed by Burken and Schnoor (1998, 1999), Newman et al. (1997), and later by Burken (2001) identified key elements about phytoremediation that focused attention on the technology. Newman et al. discussed the ability of axenic poplar cell cultures to degrade TCE. Studies where radiolabeled TCE has been applied to poplar cells or whole plants have found chlorinated compounds such as chloral, tri- and di-chloroacetic acid, and trichloroethanol. Less than 1 percent is released as carbon dioxide, and about 5 percent have been incorporated into the cell. Schnoor's work on laboratory and field demonstrations illustrated the fate and transport within the poplar plant and identified the Briggs relationship as the measure of a plant's ability to translocate compounds such as TCE effectively. The Briggs relationship shows that the efficiency of a compound's ability to cross root membrane and to be subsequently translocated, is a function of the Log Octanol Water Coeffecient (Kow) (Briggs, Bromilow, & Evans, 1982). If the log Kow is between 1.0 and 3.5, it can be taken into the plant with values in the middle range (e.g., log Kow, 2.25) being the most easily absorbed. Although more recent work by Zeeb and colleagues (Zeeb, Amphlett, Lunney, & Reimer, 2003) of the Royal Military College of Canada has shown that the upper limit could be closer to log Kow of 5.0.

Poplar Considerations

The successful use of hybrid poplars has led to outstanding claims supporting their water consumption ability and growth rate. Anyone wishing to utilize hybrid poplars for their remediation project needs to realize that there are several potential problems, and that there are still areas that need further study. In addition, many site-specific factors are critically important. First, although poplars are fast growing, they are also prone to large herbivorous insect infestations. Even mammals (e.g., deer, beaver) may cause serious damage. Second, poor agronomic conditions or contaminant toxicity may prevent or retard growth. Third, the use of identical clones (i.e., monoculture) over a site means that all poplars within that one planting area will be equally susceptible to particular pests and diseases. The extreme heterogeneity of this genus means that every clone will differ in several characteristics such as growth rate, drought tolerance, rooting characteristics, disease resistance, leaf size, stomatal distribution and response, and probably even the ability to metabolize contaminants. Therefore, just because one selected cultivar of *P. deltoides x. trichocarpa*, for example, is successful at one site, does not necessarily mean the same cultivar will be successful at a different site—or that another *P. deltoides x. trichocarpa* clone will do equally well at the original site. There are situations where species other than hybrid poplars may be more appropriate. The selection of a suitable tree species (or hybrid) and cultivar are very important.

Hybrid poplars are selected because of their quick growth and ability to degrade certain compounds.

Use and Importance of Native Plants

Hybrid poplars are selected because of their quick growth and ability to degrade certain compounds. However, they are not always long-lived and do not leave a lasting legacy for wildlife or offer other tangible environmental benefits. Site managers can address the long-term picture before leaving the project. More recently, native plants are being used in the remediation and final restoration of the site. Incorporating native species as a final step in the remediation process is now recognized to result in cost savings by reducing long-term operation and maintenance and creating self-sustaining ecosystems that enhance a site by leaving it more acceptable ecologically for habitat development.

The advantage of using native species has long been realized within the science of restoration ecology. These same benefits can be applied to phytoremediation efforts and final restoration activities. Soils at Superfund and oil spill sites are often contaminated with petroleum hydrocarbons at varying levels of contamination. Vegetation can play an important role as a polishing step in remediation, and in establishing a beneficial reuse for the site. Researchers have documented the capacity of certain native plants to tolerate the presence of petroleum (and other low-level organics) and assist in the bioremediation of these contaminated soils. Ecologically, the advantage of using native plants is straightforward; native species are adapted to the original soil conditions, tolerant to the hydrologic regime, and are integral to the local habitat. They require little initial maintenance and can become self-sustaining within three or four years.

There are two specific Executive Orders that address the protection and use of native plants. The first was signed on April 12, 1994, promoting the use of beneficial landscaping. It requires all federal agencies to use regionally native species whenever federal funds are expended for landscaping. It promotes recycling of green wastes, reducing fertilizers and pesticides, and directs agencies to create outdoor demonstration projects using native plants. The second Executive Order specifically addressed invasive species and was signed on February 3, 1999. It requires federal agencies to prevent the introduction of invasive species and to detect and respond rapidly to control established populations of invasive non-natives.

Tips for Success

The Interstate Technology Regulatory Council (ITRC) 1999 Decision Tree Document and the ITRC Technical and Regulatory Guidelines (2001) provide a means to objectively evaluate a site for phytoremediation potential. In addition, Schnoor (1997) provides a predictive method to calculate remediation time to achieve target goals and end points. These two references can be used to screen potential sites for phytoremediation potential and allow site managers to estimate the length of time involved in using a phytoremediation strategy.

> Monitoring the needs of the plants, whether they are native or exotic, is an important aspect of a phytoremediation project that cannot be overlooked.

Monitoring the needs of the plants, whether they are native or exotic, is an important aspect of a phytoremediation project that cannot be overlooked. Plants are living entities, and therefore have basic needs which must be met for them to survive and thrive, and which may change over the lifetime of the plant. Conditions may be suitable for growth of a particular plant at a particular site one year but may need considerable intervention the next due to conditions such as drought or encroachment of invasive weeds. In general, the first growing season is the most critical to a successful establishment but continued maintenance in future years can make the difference between success and failure. Moisture availability and suppression of competition (weeds) is most critical in the beginning. Due to their involvement at several actual field sites, ERT has found, through education and trial and error, several items that may contribute to success on site and other items that are superfluous or downright counterproductive. Helpful tips include:

- Control run-off and site drainage to reduce infiltration of excess rain and surface water. Clay barriers, perforated pipe, etc., should be used wherever necessary to help the plantation focus on groundwater removal.
- Conduct frequent visits to the site, especially during the first few years to ensure that trees are doing well and to intercept any problems while they are still manageable. Remove build-up leaf litter around the base of the shoot and prune suckers and dead branches. Monitor rainfall (or irrigation) to make sure that the trees are not being adversely affected by too much or too little water.
- Inspect for the presence or damage caused by insects, deer, rodents, or, worse yet, people (over-zealous gardeners armed with weedwackers and vandals). Leaf-eating caterpillars and other insect pests can be controlled chemically, biologically, or physically. Deer repellant is expensive, but aromatic soaps have been effective at reducing deer pressure at some of the sites, as is properly maintained fencing where possible.
- Cultivate the phytoremediation plants of interest as an agricultural crop. The production of this crop therefore requires attention to soil chemistry. A number of

soil samples should be obtained throughout the root zone for standard agronomic analysis such as pH, macro and micronutrients, and site contaminants. Fertilize and adjust pH annually or more frequently, if necessary, depending on soil results and recommendations. Subsurface fertilization is preferable to avoid the growth of competitive weeds.

- Plant and maintain commercial grasses or native grasses and forbs so that they are not crowding young plants. A ground cover can be effective in absorbing and removing percolating rainfall, but will suffocate live stakes and small trees.
- Mulch properly around young trees, if possible, to keep down weeds and keep moisture in the root zone. It will also keep away overly aggressive gardeners armed with weedwackers that can strip the bark off and girdle the trees. Do not, however, mulch against the trunk as this invites bark-eating rodents and diseases.

More Lessons Learned

It may not be necessary to use root barriers or deep-plant trees. These add to the cost and effort involved with the installation of the phytoremediation plots. However, deep planting does provide a quick start for the roots seeking groundwater. Lack of lateral roots may also lead to unstable trees, which may fall during windstorms. Surface water control and ground cover are more effective ways to reduce amount of unwanted clean water that enters the system. Additional lessons include:

- Avoid planting in a grid pattern. Free form plots can be aesthetically pleasing and can still be designed to achieve adequate canopy coverage.
- Avoid overcrowding trees. Allow enough room between trees for mowing, fertilizing, and other maintenance and monitoring chores.
- Install drainage systems, monitoring wells, clay layers, etc., *before* installing live stake or small trees.

Phytoremediation is a passive technology; therefore, contaminant reduction will be slow.

Phytoremediation is a passive technology; therefore, contaminant reduction will be slow. This is true especially where large reservoirs of contaminants are present in the soil or groundwater. Phytoremediation may be applied widely for many reasons. However, prudent and appropriate use can yield successful results.

Any long-term phytoremediation project will also involve monitoring to determine the effectiveness of the vegetation at reducing the contaminants of interest. Wells are installed to monitor impacts to groundwater and contaminant concentration and distribution. Understanding the soil types and hydrogeology of the site is important when dealing with contamination and the effectiveness of the phytoremediation project. Besides looking for a reduction in contaminants in soil and groundwater, ERT has frequently monitored the trees directly. Sampling of tree tissue or transpiration gases can, for example, yield contaminants, which have been removed from groundwater. Monitoring tree water use can help define how much groundwater the trees are utilizing on a daily basis (Schnoor, 1997). Low levels of contaminants may not always be detectable in tree tissue or transpiration gas, and will also vary with weather, season, tree health, and other variables. The Environmental Response Team has regularly monitored sites by obtaining soil samples, groundwater samples, air samples, tree tissue, and transpiration gas samples, and predicting tree water use.

CURRENT PHYTOREMEDIATION PROJECTS

The Environmental Response Team has been directly involved with the planning and/or monitoring of several phytoremediation sites throughout the country. Each site is unique and has provided further insight into the use of phytoremediation. Something new has been learned from every site. Current phytoremediation projects are described below, with their history, current status, and what has or has not worked well for a particular site.

J-Field, Aberdeen Proving Ground, Edgewood, Maryland

J-Field, located within the Aberdeen Proving Ground (APG), is one of the oldest and most widely studied phytoremediation sites utilizing hybrid poplars to remediate volatile organic compounds (VOCs). The site contaminants are primarily TCE and 1,1,2,2 tetrachloroethane, as well as minor amounts of breakdown products and other VOCs. J-Field is located at the tip of Gunpowder Neck River, and is partially bordered by a freshwater marsh. Historically, open pits were used for burning and detonation, eventually resulting in contamination of the soil and groundwater. Since the 1970s, J-Field has been subject to environmental investigations under the direction of the Environmental Conservation Restoration Branch of the Aberdeen Proving Ground (APG) Directorate of Safety, Health, and Environment (DSHE) Division. Groundwater flows from the former pit area into the surrounding tidal estuaries. Wells and piezometers have been installed to various depths through J-Field and sampled periodically in an effort to better characterize hydrology, formations, the contaminant plume, and the effectiveness of phytoremediation and other technologies.

Historically, open pits were used for burning and detonation, eventually resulting in contamination of the soil and groundwater.

Although many conventional remediation technologies have been proposed and implemented at J-Field, none has been particularly effective. The presence of unexploded ordnance, a low permeability aquifer, and high VOC concentrations has hindered these other efforts. The site is not accessible to the general public and there is no immediate use for the land or groundwater. This, combined with the shallow groundwater aquifer, made it an ideal site for phytoremediation. The Department of Defense and EPA jointly funded the pilot-scale application of phytoremediation and innovative treatment technologies at the facility. More details are provided in Compton, Haroski, Hirsch, and Wrobel (1998).

Almost 200 hybrid poplars (*Populus deltoides x trichocarpa* cv. H.P.510) were initially planted in March and April 1996, approximately 10 feet apart, in an area encompassing about one acre. Trees were initially deep-planted using plastic sleeves to promote downward root growth, and therefore greater utilization of groundwater. Later, excavation studies revealed these sleeves were probably not cost-effective because the soils were sufficiently tight and minimized lateral growth. Lateral root growth is restricted on the trees, but these trees appear more likely to fall during severe storm events. When trees were planted later it was decided to first drill a deep hole and refill it with loose soil to give the growing roots an easy path down towards the groundwater.

Detailed models have been created at this site utilizing hydrological data, soil type, contaminant characteristics, and tree water use to help determine phytoremediation effectiveness and time. Several parties have initiated investigation and sampling activities. Sharing this information and working together has expanded the knowledge of phytoremediation effectiveness.

Volatile organic compounds have been consistently found in transpiration gas and tree tissues sampled at this site, and appear to vary with groundwater concentration.

Contaminants of interest have been found in transpiration gas and tree tissue on at least some of the trees for several years. In recent years, more trees consistently show VOCs in the transpiration gas and tree tissue, and current efforts are being made to correlate tree tissue VOC concentrations with groundwater concentrations. In addition, cores taken at many different heights along the trunk are providing information on distribution and fate of the contaminants within the tree.

Air sampling by ERT has not revealed harmful levels of VOCs in air measurements taken at the site. Volatilization of harmful gases from the trees is minimal and diluted over time.

Sap flow rates have been measured on representative trees in different seasons using a Dynamax Dynagage TM Flow 32 system, allowing a model of water use of the plot to be produced. It has been estimated that a 23.66-liter-per-minute groundwater extraction system would be sufficient to control groundwater flow.

One unique characteristic that has led to the success of the phytoremediation project at the J-Field site is due to the low permeable aquifer. The groundwater elevation is highest in winter, and fluctuates seasonally and diurnally in summer because of evapotranspiration. An hydraulic gradient is visible during peak season, resulting in a cone of depression in the groundwater beneath the main phytoremediation area. This slows or prevents the further spread and movement of contaminants in groundwater into the surrounding marsh.

Complex models, such as MODFLOW, have been utilized to calculate low contaminant mass removal rates based on known information of contaminant levels, tree water use, hydrology, and soil types. MODFLOW calculated that the trees have demonstrated the potential to remove 360 pounds of VOCs after 30 years. A simplistic model that utilized the Transpiration Stream Concentration Factor, developed by Schnoor (1997) and Burken and Schnoor (1998), produced similar results. Using a calculated transpiration rate of vegetation, concentration of contaminants in the groundwater and soil, and rate constant of uptake, this model predicted 90 percent removal of TCE in 27 years and 90 percent removal of 1,1,2,2 tetrachloroethane in 23 years.

It is anticipated that the slower growing but long-lived native trees, such as oaks, will reach maturity as the hybrid poplars eventually decline.

Groundwater sampling has not yet yielded a reduction of contaminants at the J-Field site, but this is due to the very high levels of contaminants (e.g., 170,000 μg/l for 1,1,2,2 tetrachloroethane, 61,000 μg/l for TCE). Reduction is further hampered by the continued presence of source material on site, which needs to be further addressed. Hydraulic control at the site has, however, been a major success.

The phytoremediation potential was recently expanded with the addition of several hundred hybrid poplars as well as a mixture of several hundred indigenous native species. It is anticipated that the slower growing but long-lived native trees, such as oaks, will reach maturity as the hybrid poplars eventually decline. These additional trees will help intercept more groundwater and also intercept areas of the plume not represented by the first planting.

Edward Sears Property, New Gretna, New Jersey

Located upgradient of a tidal marsh land in the coastal plain of southern New Jersey, this 1-acre site was used from the mid-1960s to 1992 to store drums of off-specification paints, solvents, varnish, lubrication oils, tar, and epoxy resins, as well as other assorted junk and trash (Exhibit 1). An abandoned residence and small garden center currently adorn the site. In 1994 to 1995 the EPA Region II Removal Program removed and disposed of 4,000 containers ranging in size from pints to 55-gallon drums. The On-Scene Coordinator (OSC) also excavated 450 cubic yards of contaminated soil from beneath the drum storage area, to a depth of 5 feet. At this depth, a tight clay was encountered and expected to be a barrier to further penetration of the hazardous materials.

The OSC requested that ERT evaluate groundwater contamination at the site. The maximum concentrations of groundwater contaminants present on-site included: dichlormethane (470,000 µg/l), trichloromethane (510 µg/l), trimethylbenzene (1890 µg/l), xylenes (545 µg/l), and a number of other VOCs present in lower amounts. The depth to groundwater is 9 feet below ground surface (bgs). The vertical stratigraphy consists of a medium-grained sand from 0 to 5 feet, equal proportions of silt, clay, and sand from 5 to 16 feet below grade. These soils overlie a high-yield aquifer from 16 to 70 feet bgs. Soil and groundwater contamination is trapped in the lower portion of the silty, clayey, sand lense and has contaminated groundwater from 9 to 20 feet bgs. The groundwater is subject to tidal influence of about 1 foot per complete cycle.

A phytoremediation pilot study was selected for this area because of the slow migration of contaminants, the ability of roots to penetrate the silt/clay/sand lense, the lack of current groundwater users downgradient of the contaminated area, the inapplicability of pump and treat to be effective due to the high-yield aquifer being adversely affected by slow-leaching contaminants from the semiconfining layer above, and the unlikelihood that the site would receive additional cleanup funding in the near future.

Due to the small size of the site, the pilot study encompassed a large majority of the contaminated area. A separate source of petroleum contamination downgradient of the site was monitored as a positive control area, outside of the planted area. In December 1996, one hundred 12- to 16-feet tall, bare-root, hybrid poplars (*P. charkowiensis x P. incrassata*) were planted on a 100 feet by 150 feet grid. Tree spacing was 10 feet by 12.5 feet to allow access for site maintenance and sampling.

Roots were dipped in polymeric water-retentive solution to reduce planting stress and for protection from frost damage. Trees were deep-planted, with a drill rig used to bore a 12-inch diameter hole to 13 feet bgs. A 4-feet root barrier was installed, with the tree roots set at 9 to 11 feet bgs. Drill cuttings were amended with peat, crushed limestone,

Exhibit 1. The poplars at Edward Sears Property, New Gretna, New Jersey

and phosphate fertilizer based on previous analysis of soils by the county agricultural service. An attempt to use lime-stabilized sewage sludge was abandoned due to the high pH of this material. Sixty to 100 leftover poplar trees were shallow-planted around the perimeter of the site to help limit entry of clean ground and surface water into the treatment area.

Deer browsing and antler rubbing is a continuing problem at this site. Leaf-eating caterpillars initially caused significant damage to young trees and had to be controlled with physical eradication, biological means, and with pesticide application. Vandalism resulted in the loss of several microwells and "decoration" of the trees with junk from the surrounding area. Poplars in the highly contaminated area exhibited stunted growth for a few years. In recent years these trees have rebounded and reached heights similar to surrounding trees, although tree caliper has not quite caught up yet. Despite being planted in early winter and the deep-planting techniques used, a tree survival rate of 97 percent was achieved. Trees have grown very well and now exceed an average height of 36 feet (tallest trees more than 50 feet tall) and average diameter of 4.2 inches.

The extent and magnitude of all VOC contamination has been dramatically reduced over the past six growing seasons. The dichloromethane plume, with concentrations originally exceeding 470,000 µg/l, has been remediated to nondetectable levels. Trimethylbenzene reductions of 91 to 100 percent were achieved, while TCE has been reduced by 70 percent and total xylenes by 44 to 100 percent. While the contamination plume has shrunk in size, yearly reductions in remaining contaminant concentrations are still being documented. No reductions in VOCs in the untreated, positive control area were noted.

Despite being planted in early winter and the deep-planting techniques used, a tree survival rate of 97 percent was achieved.

Kauffman and Minteer, Jobstown, New Jersey

From 1960 through the 1980s it was common to see tanker trucks hauling bulk liquid plasticizers, petroleum oils, and industrial soaps enter and leave a large white building in a small rural farming community in South Jersey. The building was equipped with two large truck maintenance bays along with indoor and outdoor wash pads. Between loads, tank trucks were routinely cleaned in the truck wash bay and wash pad areas with waste liquids being discharged into a leaky drain system that led to a collection pit and drainage ditch. In addition, tank residuals were discharged into an unlined 1.3-acre lagoon built on top of a wetland area on-site. Based on the presence of chlorinated volatile organics present in soils and groundwater beneath the truck wash areas, chlorinated solvents were used to clean tanker trucks between loads.

Waste solvents, oils, soaps, and plasticizers seeped into the glauconitic, silty sands beneath the lagoon and truck wash areas. A 200-foot section of drainage ditch, downgradient of the truck wash areas also received significant contamination. The shallow contaminated soils and groundwater overlie an underlying potable aquifer that has not been contaminated.

In 1991 and again in 1997, the USEPA Region II Removal and Remedial Programs joined efforts to address the lagoon liquids and contaminated sludges and sediments in the lagoon. The lagoon was pumped dry, sludges, and heavily contaminated soils excavated (approximately 3 to 5 feet below grade), and the area was restored to the previous wetland elevation. While this effort was being conducted, an extent of contamination survey by the ERT and the Response Engineering and Analytical Contractor (REAC) revealed significant soil and groundwater contamination in the truck wash bay area. The removal program excavated contaminated vadose zone soils in the ditch area (200 feet long by 20 feet wide by 12 feet deep) in 1997 and completed excavation in the truck wash and collection pit area (100 feet long by 60 feet wide by 12 feet deep) in 1998. These areas were backfilled with medium-to-coarse sands from a local quarry.

The USEPA Removal and Remedial Programs and ERT decided to immediately implement a phytoremediation pilot study in both the lagoon area and the truck wash/collection pit/drainage ditch area to determine if this technology would be effective in containing and cleaning remaining shallow soil and groundwater contamination in the source area. This technology was chosen because it was an emerging technology that could be immediately and economically implemented, the contaminated groundwater is not imminently threatening any residential or commercial groundwater users, and the tree roots would be effective in penetrating the silty glauconitic sands and possibly obtaining hydraulic control in the source area. Also, the time frame for implementing long-term remedial action on-site was uncertain at the time.

Native black willows (*Salix nigra*) and hybrid poplars (*Populus maximowiczii x P. trichocarpa*) were planted in both the lagoon area and the drainage ditch area during the spring of 1998 (Exhibit 2). Once excavation was complete in the truck wash bay area it was also planted in the spring of 1999. Although soil cleanup and groundwater cleanup goals were met in the lagoon area, it was felt that residual soaps and oil residuals noted after excavation could be addressed by free-form planting of 48 willows and 23 poplars in this area. These trees would also enhance the habitat of the newly restored wetland.

The truck wash bay/drainage ditch area was another story. Very high concentrations of TCE (15,000 μg/l), and cis 1,2-DCE (22,000 μg/l) were present in the groundwater in this area. A more rigid 10- by 15-feet grid format was used to address these more contaminated areas, with 99 willow and 134 poplar trees placed in plots in- and downgradient of the contaminated areas. A significant effort was initially made to deep-plant 8 to 10 feet tall, bare root willows and poplars, 6 to 8 feet below grade, in sonotubes or other root barriers. The intent was to quickly force deep rooting, and enhance selective uptake of contaminated groundwater. Composted sewage sludge was blended into some of the backfill to add organic material and micronutrients. In the spring of 1999, willow live stakes were shallow-planted, as were 3-foot tall, bare root poplars. No root barriers

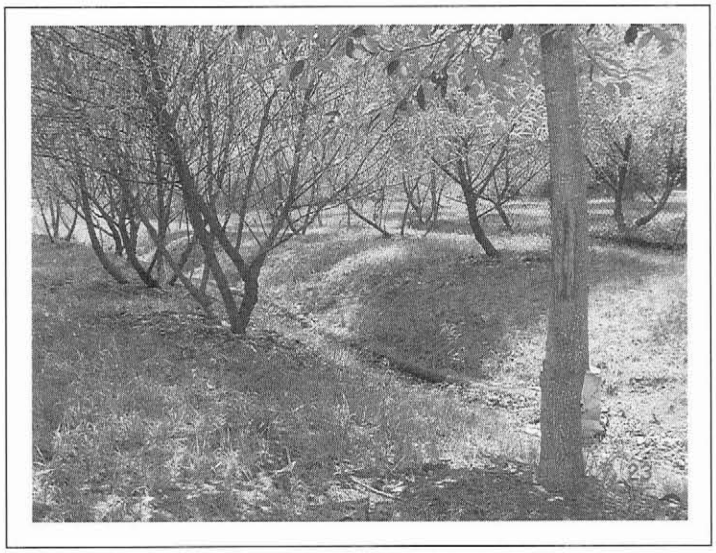

Exhibit 2. The willows at Kauffman and Minteer, Jobstown, New Jersey

were used. A total of more than 300 trees are currently being maintained at the Kauffman and Minteer site.

Heavy rains and overly aggressive string trimming resulted in the death of 45 trees in 1998. The heavy rains in conjunction with the sludge amendments caused septic conditions in the root zone, resulting in rotting of the trunk below grade. These trees were replaced with deep-planted trees without sludge amendments in the fall of 1998. Based on ERT experience with the deep-planted trees, live stake willow trees and 3-foot-tall, bare root poplar trees were planted in spring 1999, in the truck wash bay area. Drought conditions in the spring and fall of 1999 caused stress in these shallow-planted trees, particularly the willows, but they all survived. Another confounding factor in this area was the extremely low pH (4.5) of the imported backfill. Liming and watering helped to solve these problems. Deer damage and the presence of poplar leaf rollers were also continuing problems. Late frosts in 2002 severely damaged selected trees in the lagoon area. The frost mainly affected the poplar trees in the lagoon area, although almost all later recovered from basal resprouting.

Trees in the glauconitic sands are doing very well, with trunk diameters now measuring greater than 5 inches. Selected poplar trees planted in the spring of 1999 have nearly caught up to trees planted in the spring of 1998. Fresh live stakes were used to replace many dead or damaged trees. If properly watered while young, the live stakes initial rapid growth rate enables them to fill in and catch up to the overall growth of the plantation quite nicely. Frost-damaged poplar trees are also recovering quite nicely, after dead branches were removed. Initial indications of lower concentrations of contaminants in soils and groundwater, may indicate that phytoremediation plots are having a positive impact. Estimated volume of groundwater being removed is substantial in the drainage ditch area and can be expected to eventually attain hydraulic control in this area.

Trees in the glauconitic sands are doing very well, with trunk diameters now measuring greater than 5 inches.

Oregon Poplar, Clackamas, Oregon

A pilot-scale phytoremediation project had been implemented at the Oregon Department of Transportation (ODOT) Oregon Poplar Site, in Clackamas County, Oregon, in 1997. The exact source of the contaminants on this property is unknown, but it is probably the result of illegal dumping activities. The area of interest comprises approximately 3 to 4 acres within an otherwise vacant land parcel. A small stream runs parallel to the southwest boundary of the planted area, downgradient of the contaminated soil and groundwater.

The site had been an abandoned, grassy field for many years prior to commencement of the phytoremediation project. Contaminants of concern at the site are primarily VOCs, including PCE, TCE, cis-1,2-dichloroethene (c-DCE), 1,1-dichloroethane (DCA), 1,1- dichloroethene (DCE), vinyl chloride (VC), benzene, toluene, ethylbenzene, and xylene. It is estimated that 8,100 cubic yards of contaminated soil was excavated from the site in 1995 as part of an interim remedial action measure. There has been no pressure to develop this parcel for immediate land use.

The county expressed the future anticipated land use for this site to be a park or other location of recreational activity. Subsequently, the county specifically requested that the phytoremediation design incorporate native trees and not be planted in typical corn rows. This reasonable request would not interfere with the overall effectiveness of the technology. As a result, a combination of native and hybrid poplars were used in a random block design to provide a more natural setting for their park.

The shallow groundwater at the site historically was measured between 2 and 10 feet bgs and varies with seasonal precipitation. Shallow soils are made up of silty clay to depths of about 10 feet bgs. Below this silty clay is 15 to 20 feet of poorly sorted gravel-to-cobble, with hydraulic conductivity ranging from 2 to 10 feet/day in the gravel and 0.1 to 3 feet/day in the silty clay. The shallow groundwater is locally confined beneath the site and is in hydraulic contact with the creek.

Based on the above criteria, it was determined that this particular site would be ideal for use in a phytoremediation demonstration project. The Oregon Department of Transportation was responsible for the land and oversaw the initial site preparation, while a contractor developed the design and installed the plant material. The Environmental Response Team and REAC provide technical support and oversight of the project. A contractor provided and planted the trees using 12-to18-inch dormant hardwood cuttings or live stakes. Two hybrid poplar clones (*P. deltoides x trichocarpa*) and two clones of a native poplar species were installed. It was originally suggested that large blocks of the same clone be planted together for future comparison of growth and phytoremediation capabilities.

Further monitoring is needed at this site, but the trees have done well and are removing contaminants.

The Oregon Department of Transportation personnel returned to the site in the summer of 2002. The Oregon Department of Transportation has continued to maintain the plot and attend to the trees. Different areas of the plot show different growth patterns (see below), which may be the direct result of different clones or different soil or groundwater conditions. The largest trees at the site have done extremely well, attesting to the good poplar growing conditions found in the Pacific Northwest. The larger poplars within the plot had trunk diameters more than 4 inches at breast height. Although the groundwater at the site had not been sampled for some time, tree tissue and transpiration gas samples were obtained from selected larger trees growing in areas that had historically demonstrated high groundwater VOC levels.

Trichloroethylene, PCE, and/or cis-1,2-dichloroethylene were found in the tissue or transpiration gas of three of the four trees examined in 2002, indicating that the trees are utilizing groundwater or soil contaminated with these compounds. Tetracholorethylene was conservatively measured at 1,500 μg/kg dry weight in trunk tissue of one of the trees. Groundwater was not sampled at this time but it is anticipated that the groundwater will be sampled in 2003 by another subcontractor, revealing whether or not groundwater concentrations are declining and if the contaminant groundwater plume has changed. Additional wells may need to be installed to further define the plume.

Further monitoring is needed at this site, but the trees have done well and are removing contaminants. This site is ideal because of the excellent poplar growing conditions found in the Pacific Northwest, shallow groundwater, contaminant type, and low risk posed by contaminants. The site is well maintained by the Oregon Department of Transportation, which is interested in the effectiveness of the technology. And so the county will soon have a lush park.

Naples Truck Stop Site, Naples, Utah

The Naples Truck stop site was a retail petroleum distributor that is now vacant. In 1993 a tank and line monitoring alarm at Questar Pipeline Company, a trucking company adjacent to Naples Truck Stop, made Questar aware of a leak of more than 7,000 gallons of unleaded gasoline from an underground pipe. The EPA Region VIII responded by installing groundwater wells at both properties. The Army Corps of Engineers (ACE) installed an active groundwater treatment system (vacuum enhanced/biotreatment, thermal oxidizer unit, and granular-activated carbon-filtration unit) in March 1994 that operated until 1998. The Environmental Response Team visited the site with the EPA site manager. A dilemma at this site was that the pump and treat operation had reached the "marginal rate of return" such that it no longer cost-effectively removed the LNAPL; however, there remained significant levels of dissolved phase gasoline constituents in the groundwater.

In 1998 ERT/REAC installed a passive phytoremediation system. Limited property access forced the planting design to follow property boundaries and municipal rights of way. After much discussion regarding implementation, a local landscape contractor recommended a fast-growing native Siouxland Poplar for the project. The town of Naples receives approximately 6 inches of precipitation per year and the depth to groundwater at the site varied throughout the season from 3 feet to 10 feet bgs. Many gasoline constituents have log Kows within the 1.0 to 3.5 range. Aside from the planting area limitation, given the above site characteristics and low ecological risk, this site was ideal for phytoremediation.

Phytoremediation is still in its infancy and there are still many knowledge gaps, but it has shown to be effective at several sites under varied field conditions

In the late fall of 1998, 600 two-year-old (approximately 10 feet tall by 1.5 to 2 inches diameter at breast height) poplars were shallow planted opportunistically along rights of way in concert with an irrigation system that would provide both water and nutrients for the first two years. Within four years the trees were 40 feet tall.

The trees looked great the first two years until some unknowing maintenance workers sprayed the soils around a back row of trees with a potent and persistent herbicide. About 50 trees were lost and those replanted are still struggling with the long half-life of the chemical. In addition, the planting area limitations were restrictive and in the periphery of the plume. Ideally 1,000 trees cluster planted on, and downgradient of the plume would have been better.

The good news is the gasoline constituent levels are decreasing in the groundwater. There is variability in the data; however, there is a clear trend from the consistently hottest well MW-10 from October 1998 of 25,000 µg/l TPH to 2000 µg/l TPH and an intermediate well MW-8, 2200 µg/l TPH to 320 µg/l TPH. The variability in the groundwater has been due to the volume of pumping for irrigation during growing season. Therefore, a measure of the piezometric surface to assess degree of hydraulic control imparted by the plantation has not been successful. The groundwater concentration reductions could be attributed to rhizosphere microbially enhanced degradation. No detectable concentrations of COCs were found in the near field air.

CONCLUSION

In summary, phytoremediation has been implemented with varying degrees of success at several Superfund sites throughout the United States. Knowledge and information applicable to future success have been obtained from many of these sites.

Phytoremediation is still in its infancy and there are still many knowledge gaps, but it has shown to be effective at several sites under varied field conditions. Every site is unique and carries its own idiosyncrasies, problems, and benefits. Because phytoremediation, by definition, utilizes living plants, it is important that suitable plants are selected and conditions on site are provided so that these plants will thrive and grow. Many phytoremediation sites also provide an opportunity to utilize native plant species. When applicable, phytoremediation provides a green solution, which can be very effective, and also aesthetically pleasing to the local community. From experience at several sites, ERT has developed an effective maintenance and monitoring program and can provide insight into future site work.

ACKNOWLEDGMENTS

The authors would like to thank Dr. Royal Nadeau, formerly the Deputy Director of ERT, for his wisdom and support for restoration and revegetation activities over the past decade. Dr. Nadeau was an encouraging mentor to each of us. He is a true visionary for the use of plants to repair damaged lands and was an effective advocate for undertaking innovative projects within the scope of government operations. Dr. Nadeau currently pursues his passion for restoration and revegetation as a certified Senior Ecologist with the Eco-Strategies Group in Allamuchy, NJ (www.theeco-strategiesgroup.com).

REFERENCES

Anderson, T.A., & Walton, B.T. (1995). Comparative fate of [14c] trichloroethylene in the root zone of plants from a formal disposal site. Environmental Toxicology and Chemistry, 14, 2041–2047.

Briggs, G.G., Bromilow, R.H., & Evans, A.A. (1982). Relationships between lipophilicity and root uptake and translocation of non-ionised chemicals by barley. Pesticide Science, 13, 495–504.

Burken, J.G. (2001, June). Uptake and volatilization of chlorinated solvents by poplars at field-scale. Preprint of paper presented at the Sixth International Conference on In Situ and On-Site Bioremediation, San Diego, CA.

Burken, J.G., & Schnoor, J.L. (1998). Predictive relationship for uptake of organic contaminants by hybrid poplar trees. Environmental Science and Technology, 32, 3379–3385.

Burken, J.G., & Schnoor, J.L. (1999). Distribution and volatilization of organic compounds following uptake by hybrid poplar trees. International Journal of Phytoremediation, 1(2), 139–151.

Compton, H.R., Haroski, D.M., Hirsch, S.R., & Wrobel, J.G. (1998). Pilot-scale use of trees to address voc contamination. In G.B. Wickramanayake & R.E. Hinchee (Eds.), Proceedings of the International Conference on Remediation of Chlorinated and Recalcitrant Compounds (Vol. 4, pp. 245–250). Monterey, CA. Battelle Press.

Interstate Technology and Regulatory Cooperation Work Group. Phytoremediation Work Team. (1999). Phytoremediation decision tree. Document no. PHYTO-1. Interstate Technology and Regulatory Cooperation Work Group, 1999. Retrieved from http://www.itrcweb.org/phyto_1.pdf [2003, March 14].

Interstate Technology and Regulatory Cooperation Work Group. Phytoremediation Work Team. (2001). Technical and Regulatory Guidelines. Document no. PHYTO-2. Interstate Technology and Regulatory Cooperation Work Group, 2001 [Online]. Retrieved from http://www.itrcweb.org/phyto_2.pdf [2003, March 14].

Newman, L.A., Strand, S.E., Choe, N., Duffy, J., Ekuan, G., Ruszaj, M., Shurtleff, B.B., Wilmoth, J., Heilman, P., & Gordon, M.P. (1997). Uptake and biotransformation of trichloroethylene by hybrid poplars. Environmental Science and Technology, 31(4), 1062–1067.

Schnoor, J. (1996). Environmental modeling fate and transport of polutants in water, air, and soil. New York: John Wiley & Sons, Inc.

Schnoor, J.L. (1997). Phytoremediation. Technology Evaluation Report, E series: TE-98-01. Pittsburgh: Ground-Water Remediation Technologies Analysis Center.

U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response. (2000, September). Newman, L.A. Phytoremediation of groundwater contaminants. groundwater currents, no. 37, EPA 542-B00-006. Washington, DC: Author. Retrieved from http://www.epa.gov/tio/download/newsltrs/gwc0900.pdf [2003, March 14].

U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response-Technology Innovation Office. (1998). A citizen's guide to phytoremediation. Technology Fact Sheet, EPA 542-F-98-011. Washington, DC: Author.

Zeeb, B.A., Amphlett, J.S., Lunney, A., & Reimer, K.J. (2003, March). The potential for phytoremediating PCBs and DDT. Paper presented at the USEPA International Applied Phytotechnologies Conference, Chicago, IL.

Harry R. Compton is an environmental engineer who has been with the EPA Environmental Response Team for 18 years, providing technical assistance in the Superfund Program. His current focus includes implementing EPA priorities of revitalization of sites by employing scientifically sound, cost-effective, publicly acceptable technologies. An advocate of green engineering, he has been implementing phytoremediation and mine site reclamation for the past six years.

George R. Prince is an environmental scientist who has been with the EPA Emergency Response Team for more than 20 years, developing innovative approaches to investigate and clean up hazardous waste sites nationwide. He has played an integral part in the development and field testing of emerging technologies, including x-ray fluorescence, soil gas, field GC for soils and groundwater analysis, phytoremediation, and more recently, in-situ chemical oxidation and thermally enhanced SVE.

Scott C. Fredericks is a biologist who has been with EPA for 27 years, providing technical assistance in the Superfund Program. His current focus is on the restoration/revegetation of sites, particularly mine-damaged land that incorporates the use of native plants. An advocate of using biosolids and other residuals, he has been implementing phytoremediation and mine site reclamation for the past six years.

Christopher D. Gussman is currently the Engineering Group Leader at Lockheed Martin/REAC involved with several USEPA/ERT phytoremediation, restoration, and revegetation projects. He is experienced in plant research, molecular biology, phytoremediation, commercial horticulture production, restoration, ecology, and plant physiology.