Phytoremediation of Petroleum Hydrocarbons

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ACRONYMS & INITIALISMS

ATSDR	Agency for Toxic Substances and Disease Registry
AEHS	Association for Environmental Health and Sciences
bgs	below ground surface
BTEX	benzene, toluene, ethylbenzene, and xylenes
DNAPL	dense non aqueous phase liquid
DOE	U.S. Department of Energy
DRO	diesel-range organics
EPA	U.S. Environmental Protection Agency
ft	feet
GRO	gasoline-range organics
m	meter
mg/kg	milligrams per kilogram
mg/L	milligrams per liter
MTBE	methyl tert butyl ether
ND	not detected
NEBA	net environmental benefit analysis
PAH	polycyclic aromatic hydrocarbon
PCB	polychlorinated biphenyl
pCi/L	picocuries per liter
RTDF	Remediation Technologies Development Forum
SITE	Superfund Innovative Technology Evaluation
TMB	trimethylbenzene
TPH	total petroleum hydrocarbons
µg/L	micrograms per liter
VOC	volatile organic compound

1. INTRODUCTION TO PHYTOREMEDIATION

Phytoremediation is a broad term that has been in use since 1991 to describe the use of plants to reduce the volume, mobility, or toxicity of contaminants in soil, groundwater, or other contaminated media (McCutcheon 2003).

For at least 300 years, the ability of plants to remove contaminants from the environment has been recognized and taken advantage of in applications such as landfarming of waste. Over time, this use of plants has evolved to the construction of treatment wetlands or even the planting of trees to counteract air pollution. In more recent years, as recognition grew of the damage resulting in the United States and around the world from decades of an industrial economy and extensive use of chemicals, so did interest in finding technologies that could address the residual contamination, among them phytoremediation (McCutcheon 2003).

Research into and application of phytoremediation has flourished over the last 15 years. Phytoremediation has been implemented as a component of the selected remedy at 18 Superfund sites in the United States (Kovalick 2005). Since 2001, the International Journal of Phytoremediation has been published quarterly. An international conference devoted to phytoremediation work has been convened seven times. In this same time period, public and private dollars have been funneled into research at the laboratory, greenhouse, and field scale to understand both the mechanisms by which plants address existing contamination and to establish the actual remediation performance of various plant species in different media and contaminants.

Although phytoremediation may not be the perfect remedial solution that some envisioned when its use at hazardous waste sites was first pioneered, its implementation continues to be appropriate or even preferable at a variety of sites. As the technology matures and its use expands beyond research laboratories and government-funded remediation, site owners and consultants will want comparative data on phytoremediation to determine its appropriateness for a particular site. The purpose of this report is to compile existing data for such an evaluation.

1.1. Mechanisms

Researchers have identified mechanisms by which plants can affect contaminant mass in soil, sediments, and water. Although overlap or similarities can be observed between some of these mechanisms, and the nomenclature varies, this report makes reference to seven phytoremediation mechanisms, each explained in detail below: phytoextraction, phytovolatilization, phytodegradation, rhizodegradation, rhizofiltration, phytostabilization, and hydraulic control.

Each of these mechanisms will have an effect on the volume, mobility, or toxicity of contaminants, as the application of phytoremediation is intended to do (EPA 2000b).

- Phytoextraction: The first phytoremediation patent applied for in the United States related to phytoextraction (McCutcheon 2003). Phytoextraction refers to the ability of plants to remove metals and other compounds from the subsurface and translocate them to the leaves or other plant tissues. The plants may then need to be harvested and removed from the site. Even if the harvested plants must be landfilled, the mass disposed of is much smaller than the original mass of contaminated soil. Use of phytoextraction is usually limited to metals and other inorganic compounds in soil or sediment (EPA 2000b).

- Phytovolatilization: Phytovolatilization also involves contaminants being taken up into the body of the plant, but then the contaminant, a volatile form thereof, or a volatile degradation product is transpired with water vapor from leaves (EPA 2000b). Phytovolatilization may also entail the diffusion of contaminants from the stems or other plant parts that the contaminant travels through before reaching the leaves (McCutcheon 2003). Phytovolatilization can occur with contaminants present in soil, sediments, or water and has been found to occur with volatile organic compounds, including trichloroethene, as well as inorganic chemicals that have volatile forms, such as selenium, mercury, and arsenic (EPA 2000b).

- Phytodegradation: When the phytodegradation mechanism is at work, contaminants are broken down after they have been taken up by the plant. As with phytoextraction and phytovolatilization, plant uptake generally occurs only when the contaminants' solubility and hydrophobicity fall into a certain acceptable range. Phytodegradation has been observed to remediate some organic contaminants, such as chlorinated solvents, herbicides, and munitions, and it can address contaminants in soil, sediments, or groundwater (EPA 2000b).

- Rhizodegradation: Rhizodegradation refers to the breakdown of contaminants within the plant root zone, or rhizosphere. Rhizodegradation is believed to be carried out by bacteria or other microorganisms whose numbers typically flourish in the rhizosphere. Studies have documented up to 100 times as many microorganisms in rhizosphere soil as in soil outside the rhizosphere (McCutcheon 2003). Microorganisms may be so prevalent in the rhizosphere because the plant exudes sugars, amino acids, enzymes, and other compounds that can stimulate bacterial growth. The roots also provide additional surface area for microbes to grow on and a pathway for oxygen transfer from the environment. The localized nature of rhizodegradation means that it is primarily useful in contaminated soil, and it has been investigated and found to have at least some success in treating a wide variety of mostly organic chemicals, including petroleum hydrocarbons, polycyclic aromatic hydrocarbons (PAHs), chlorinated solvents, pesticides, polychlorinated biphenyls (PCBs), and benzene, toluene, ethylbenzene, and xylenes (BTEX) (EPA 2000b).

- Rhizofiltration: In the rhizofiltration process, contaminants are also taken up by the plant and removed from the site when the plant is harvested; however, in this case, the contaminant is removed from the dissolved phase and concentrated in the root system. Rhizofiltration is typically exploited in groundwater (either in situ or extracted), surface water, or wastewater for removal of metals or other inorganic compounds (EPA 2000b).

- Phytostabilization: Phytostabilization takes advantage of the changes that the presence of the plant induces in soil chemistry and environment. These changes in soil chemistry may induce adsorption of contaminants onto the plant roots or soil or cause metals precipitation onto the plant root. The physical presence of the plants may also reduce contaminant mobility by reducing the potential for water and wind erosion. Phytostabilization has been successful in addressing metals and other inorganic contaminants in soil and sediments (EPA 2000b).

- Hydraulic control: Phytoremediation projects employing hydraulic control generally use phreatophytic trees and plants that have the ability to transpire large volumes of water and thereby affect the existing water balance at the site (McCutcheon 2003). The increased transpiration reduces infiltration of precipitation (thereby reducing leaching of contaminants from the vadose zone) or increases transpiration of groundwater, thus reducing contaminant migration from the site in groundwater plumes. Hydraulic control can therefore be used to address a wide range of contaminants in soil, sediment, or groundwater (EPA 2000b).

The success of phytoremediation at a given site cannot always be attributed to just one of these mechanisms because a combination of mechanisms may be at work.

1.2. Evaluating Phytoremediation as a Potential Remediation Technology

In the traditional Superfund or similar remediation process, a risk assessment may be performed to evaluate what human health or ecological risks exist at a site and how potential remedial options may address them (DOE 2003). Remedial options are compared against one another, and an innovative remediation technology, such as phytoremediation, must offer advantages in terms of either risk reduction or cost savings over excavation and landfilling of contaminated material or other traditional techniques to be implemented at a site. Although not comprehensive, some of the benefits and limitations of phytoremediation are described here.

1.2.1. Benefits of Phytoremediation

Numerous benefits of phytoremediation have been established or hypothesized:

- Phytoremediation can be less invasive and destructive than other technologies.
- Studies have indicated that implementing phytoremediation may result in a cost savings of 50 to 80 percent over traditional technologies (EPA 2000b).
- Phytoremediation may provide habitat to animals, promote biodiversity, and help speed the restoration of ecosystems that were previously disrupted by human activity at a site (EPA 2000b; DOE 2003; Wilson 2004).
- Phytoremediation installations can improve the aesthetics of brownfields or other contaminated sites.
- Phytoremediation may promote better air or water quality in the vicinity of the site (Wilson 2004).
- Vegetation may help reduce erosion by wind or water (Wilson 2004).
- Planted trees may also provide shade to buildings, helping to decrease energy consumption (Nowak 2002).
- Forests and other vegetation serve as a carbon sink to help sequester carbon emitted from other sources.

1.2.2. Limitations of Phytoremediation

Phytoremediation is not universally appropriate or successful; some important limitations must be noted:

- Extremely high contaminant concentrations may not allow plants to grow or survive; phytoremediation is likely to be more effective or reasonable for lower concentrations of contaminants (EPA 2000b).
- For remediation to be successful, contamination must generally be shallow enough that plant roots can reach the contaminants, or contamination must be brought to the plant (EPA 2000b).
- Phytoextraction techniques can cause contaminants to accumulate in plant tissues, which could cause ecological exposure issues or require harvesting (EPA 2000b).
- Phytovolatilization may remove contaminants from the subsurface, but might then cause increased airborne exposure (EPA 2000b).
- If non-native species are selected for phytoremediation, the consequences of introducing them to the ecosystem may be unknown or unexpected (EPA 2000b).
- The time required to achieve the remedial goals may be longer with phytoremediation than with other treatment technologies. Phytoremediation can require several growing seasons for a tree stand to be established and for contaminant concentrations to be reduced (EPA 2000b).

1.2.3. Quantifying Phytoremediation Benefits and Limitations

One of the problems with the traditional approach to evaluating remedial options is that an alternative like soil excavation may appear desirable because the removal of contaminants from a site will likely accomplish remediation goals. Unfortunately, this approach may also destroy any remaining ecosystem at the site or have other negative impacts that are not accounted for in a risk or cost-benefit analysis (DOE 2003).

The limitation of the traditional approach has become even more glaring as the objective of remediation has evolved in recent years. As an example, the U.S. Environmental Protection Agency (EPA) announced a "Land Revitalization Initiative" in 2003 to encourage remediation efforts that not only protect human health and the environment but also prepare formerly contaminated sites for eventual reuse (EPA 2003a). This shift in approach may also require a change in the framework employed for evaluating remedial options, reaching beyond the consideration of human health or ecological risks to considerations of "the long term social and ecological benefits of ecological restoration and revitalization efforts" (Wilson 2004).

A 2003 U.S. Department of Energy (DOE) report encourages the use of a net environmental benefit analysis (NEBA) to evaluate the balance between the improvements in ecosystem services—that is, "the benefits people obtain either directly or indirectly from ecological systems"—that a remedial alternative will cause and the negative effects of the same alternative. NEBA requires that the effects of each remedial alternative, both positive and negative, be quantified to identify the alternative with the highest net benefit so that a remedy can be selected for implementation (DOE 2003; Wilson 2004). The principle behind NEBA is that restoration of contaminated sites to the highest possible net benefit in terms of ecosystem services is socially, environmentally, and *economically* beneficial to American society, and this belief seems to fit closely with the Land Revitalization Initiative discussed previously (Wilson 2004).

The DOE report recognizes that at sites with petroleum hydrocarbon contamination, phytoremediation may become an attractive alternative in the NEBA context because in addition to enhancing the degradation of the hydrocarbons, planting vegetation may provide ecological benefits that outweigh those of excavation or other remedial options (DOE 2003). Unfortunately, these ecosystem services are often overlooked in the selection of a remedy (Wilson 2004).

As an example, one benefit that phytoremediation can offer that might not be considered in a traditional evaluation is the ability of trees and other vegetation to sequester carbon from the atmosphere and serve as a carbon sink. In the NEBA framework, carbon sequestration would be considered a "Regulating Service," that is, a way in which "ecosystems regulate essential ecological processes and life support systems" (Wilson 2004).

During photosynthesis, trees and other plants consume atmospheric carbon dioxide, eventually converting it to sugars and other compounds and storing excess carbon in the plant biomass (Nowak 2002). Trees will sequester carbon from the atmosphere as long as they are growing (EPA 2004). Carbon may also be sequestered from the atmosphere and stored as organic carbon in soil (West 2002), which may account for as much as 60 percent of the total carbon stored in a forest system (Nowak 2002). When a tree reaches maturity, it will continue to store the already sequestered carbon until it is harvested or dies. Upon harvesting, it will emit carbon back into the atmosphere either immediately, if incinerated, or over a long period of time if used in wood products or placed in a landfill. If the tree dies before being harvested, the stored carbon may be released back to the atmosphere as the tree biomass decays or may be incorporated into soil organic carbon (EPA 2004).

Although carbon sequestration varies with species, soil type, planting density, and other factors, it has been estimated that nationally trees sequester approximately 0.21 kilograms of carbon per square meter per year or approximately 0.94 tons of carbon per acre per year (EPA 2004). In 2002, trees, other vegetation, soil, and wood products both currently in use and in landfills were estimated to have sequestered a total of 690,723 gigagrams (or 6.90×10^{14} grams) of carbon dioxide nationally, which offset more than 12 percent of the total 5,782,363 gigagrams emitted in the United States that year (EPA 2004). Phytoremediation projects may be able to contribute to the increased carbon sequestration by vegetation and soil, although the environmental and economic effects on the scale of a single phytoremediation project may be challenging to quantify.

1.3. Implementation of Phytoremediation

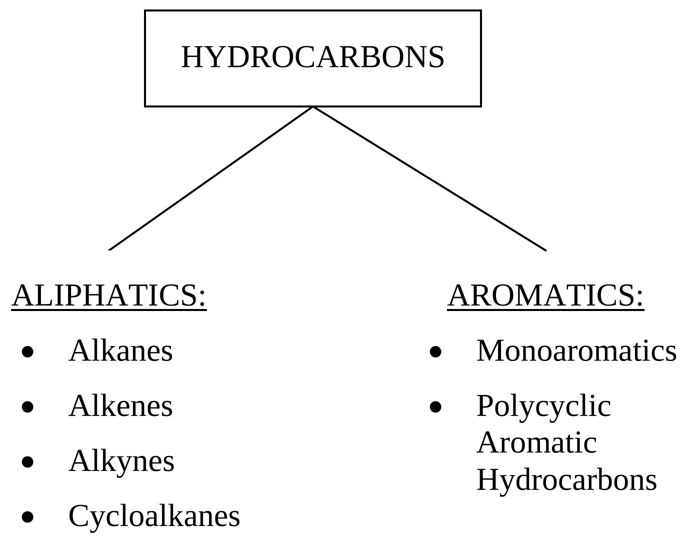
As should be apparent from the benefits and drawbacks to phytoremediation listed above, the success of phytoremediation at a given site is dependent on a large number of factors, including contaminant types, concentrations, and depths; contaminated media; selection of appropriate vegetation; plant growth and survival; and site climate. As with all remediation projects, a thorough feasibility study and analysis of remedial options is typically warranted before selection of phytoremediation as the final remedy.

Once phytoremediation has been selected, greenhouse studies, pilot testing, or even field demonstrations may be required before a full-scale system can be installed. Careful consideration should be given to plant selection, operation and maintenance requirements (including fertilization and irrigation), and performance monitoring to ensure that the remedy is effective.

2. OVERVIEW OF PETROLEUM HYDROCARBONS

Petroleum hydrocarbons present a challenge both in the understanding of their chemical behavior and in remediation design because they comprise hundreds of compounds. Figure 1 shows the general categories of hydrocarbon constituents.

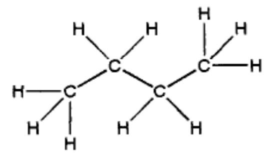
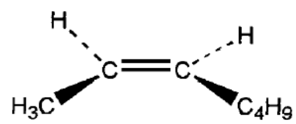
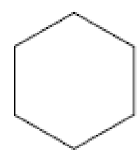
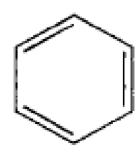
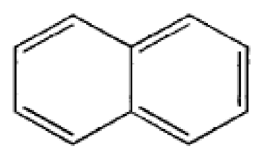
Figure 1.
Schematic of Hydrocarbon Categories



Source: Adapted from AEHS (1998b).

The two primary categories of hydrocarbons, aliphatics and aromatics, are divided up based on the general chemical structure of their constituent chemicals. Aliphatics contain chains of carbon atoms strung together, while aromatics contain one or more benzene rings bonded together (AEHS 1998b). Table 1 summarizes the various compounds and gives examples of each.

Table 1.
Chemical Structures of Various Categories of Hydrocarbons

Category	Description	Example Chemical Structure
Aliphatics		
Alkanes	Carbon chain with single bond between carbon atoms	n-Butane 
Alkenes	Carbon chains with at least one carbon-carbon double bond	cis-2-Heptene 
Alkynes	Carbon chains with at least one carbon-carbon triple bond (not commonly found in petroleum hydrocarbons)	1-Butyne $HC \equiv CCH_2CH_3$
Cycloalkanes	Single-bonded carbon ring structure	Cyclohexane 
Aromatics		
Monoaromatics	Primary structure is the benzene ring made up of six carbon atoms with alternating single and double bonds	Benzene 
PAHs	A compound having two or more benzene rings fused together	Naphthalene 

Adapted from AEHS (1998a and 1998b).

2.1. Typical Sources and Uses of Petroleum Hydrocarbons

Petroleum products are usually produced from crude oil by distillation, a process that separates various petroleum fractions by their boiling points. Petroleum hydrocarbons found in the environment typically originate from crude oil and common crude oil distillates like gasoline, diesel, lubricating oil, and other typical petroleum products (AEHS 1998a).

Gasoline typically comprises the C_4 to C_{12} crude oil fraction that has a relatively low boiling point (less than 200°C) blended with other refined petroleum products. One estimate indicates that gasoline is typically made of 40 to 70 percent alkanes and cycloalkanes, less than 10 percent alkenes, and 20 to 50 percent aromatics, including BTEX and the two-ringed PAH, naphthalene (AEHS 1998a and 1998b).

Diesel, on the other hand, generally consists of middle end distillates (generally crude oil fractions with boiling points between 200 and 300°C) of crude oil blended with longer chain (and higher boiling point) fuel oils that have been "cracked" to produce smaller molecules (AEHS 1998a). Hydrocarbons in diesel tend to be in the C_8 to C_{26} range, with 60 to 90 percent alkanes and cycloalkanes, less than five percent alkenes, and 10 to 30 percent aromatics (AEHS 1998a; Trapp 2001).

While PAHs may be constituents of crude oil and refined petroleum products, they are also widespread in the environment because they are produced by incomplete combustion of coal, oil, wood, or other organic matter (ATSDR 2004; Kanaly 2000).

It should be noted that "total petroleum hydrocarbons" (TPH) is identified as the contaminant of interest at many of the sites included in Appendix A. While soil or groundwater samples at a site can be analyzed for a specific compound like the concentration of benzene or naphthalene, TPH is a vaguer term that measures the total carbon compounds with reference to a specific calibration standard, usually employing an infrared technique; however, the true total value of all hydrocarbons of all carbon-chain lengths cannot be measured with a single technique. The carbon range specified in each case depends on the analytical method used to evaluate soil or groundwater samples at the site (AEHS 1998a). Some sites use gas chromatography methodologies to identify "gasoline-range organics" (GRO) or "diesel-range organics" (DRO), which refer to narrower ranges of hydrocarbons but are not rigorously defined.

2.2. Physical/Chemical Properties and Weathering Processes

The sheer number of compounds that are considered petroleum hydrocarbons makes generalizations about their physical and chemical properties challenging. Table 2 summarizes some important physical and chemical properties of individual constituents, including the BTEX compounds and some PAHs. Chemical properties for certain carbon ranges have also been estimated and are provided.

Table 2.
Chemical Properties of Selected Hydrocarbon Constituents

Chemical Name	Chemical Formula	Molecular Weight (g/mol)	Water Solubility (mg/L)	Octanol-Water Partition Coefficent (log K_{ow})	Organic Carbon Partition Coefficient (K_{oc})	Henry's Law Constant
Aliphatic Ranges						
EC 5-6	--	81	36	NA	2.9	33
EC >6-8	--	100	5.4	NA	3.6	50
EC >8-10	--	130	0.43	NA	4.5	80
EC >10-12	--	160	0.034	NA	5.4	120
EC >12-16	--	200	0.00076	NA	6.7	520
EC >16-21	--	270	2.50E-06	NA	8.8	4900
Aromatic Ranges						
EC >8-10	--	120	65	NA	3.2	0.48
EC >10-12	--	130	25	NA	3.4	0.14
EC >12-16	--	150	5.8	NA	3.7	0.053
EC >16-21	--	190	0.65	NA	4.2	0.013
EC >21-35	--	240	0.066	NA	5.1	0.00067
BTEX Compounds						
Benzene	C_6H_6	78.1	1,780	2.13	81.2	0.23
Toluene	C_7H_8	92.1	515	2.69	234	0.27
Ethylbenzene	C_8H_{10}	106.2	152	3.13	537	0.36
m-Xylene	C_8H_{10}	106.2	160	3.2	612	0.30
p-Xylene	C_8H_{10}	106.2	215	3.18	590	0.23
o-Xylene	C_8H_{10}	106.2	220	3.15	557	0.23
Polycyclic Aromatic Hydrocarbons						
Acenaphthene	$C_{12}H_{10}$	154.21	3.8	3.92	2,380	0.00491
Acenaphthylene	$C_{12}H8$	152.2	16.1	4.00	2,770	0.00339
Anthracene	$C_{14}H_{10}$	178.2	0.045	4.54	7,690	0.00160
Benzo[a]anthracene	$C_{18}H_{12}$	228.3	0.011	5.91	1.02E+05	0.000234
Benzo[a]pyrene	$C_{20}H_{12}$	252.3	0.0038	6.04	1.31E+05	1.86E-05
Benzo[b]fluoranthene	$C_{20}H_{12}$	252.32	0.0015	5.8	83,000	NA
Benzo[e]pyrene	$C_{20}H_{12}$	252.3	0.004	6.44	2.78E+05	8.07E-06
Benzo[g,h,i]perylene	$C_{22}H_{12}$	268.36	0.0003	6.50	3.11E+05	3.03E-05
Benzo[j]fluoranthene	$C_{20}H_{12}$	252.32	6.76E-03	6.12	NA	1.00E-06 atm-m^3/mol
Benzo[k]fluoranthene	$C_{20}H_{12}$	252.32	0.0008	6.00	1.21E+05	6.46E-06

Chemical Name	**Chemical Formula**	**Molecular Weight (g/mol)**	**Water Solubility (mg/L)**	**Octanol-Water Partition Coefficent (log K_{ow})**	**Organic Carbon Partition Coefficient (K_{oc})**	**Henry's Law Constant**
Chrysene	$C_{18}H_{12}$	228.3	1.50E-03	5.79	8.14E+04	0.000180
Dibenz[a,h]anthracene	$C_{22}H_{14}$	278.35	5.00E-04	6.84	NA	7.3E-08 atm-m^3/mol
Fluoranthene	$C_{16}H_{10}$	202.26	0.26	5.22	27,800	0.000417
Fluorene	$C_{13}H_{10}$	166.2	1.9	4.18	3,900	0.00319
Indeno[1,2,3-c,d]pyrene	$C_{22}H_{12}$	276.3	0.062	7.00	8.00E+05	2.07E-11
Naphthalene		128.19	31	3.37	844	0.0174
Phenanthrene	$C_{14}H_{10}$	178.2	1.1	4.57	8,140	0.00131
Pyrene	$C_{16}H_{10}$	202.3	0.132	5.18	2.57E+04	0.000371

Sources: AEHS (1997a) and ATSDR (2004).

Some of the important properties of hydrocarbons can be thought of in terms of their susceptibility to the natural weathering processes that petroleum hydrocarbons undergo with time when they are released to the environment. Among the most important of these are volatilization, leaching into water, and microbial degradation (AEHS 1998b). Although rates of weathering certainly depend on the nature of the environment in which the hydrocarbon exists, there is also great dependence on the physical and chemical properties of the hydrocarbon constituents themselves (AEHS 1998a).

Compounds with lower boiling points—that is, constituents of the low end and middle distillates—will tend to be more volatile, including many gasoline and even diesel constituents (AEHS 1998a; Trapp 2001). Generally, the aliphatic compounds are more volatile than aromatics, and volatility declines with increasing molecular weight (AEHS 1998b).

The more soluble and less hydrophobic compounds will be most susceptible to leaching processes. Water solubility of these compounds, however, depends on their polarity. Since the electrons within the aromatic ring structure are delocalized, aromatic hydrocarbons tend to be somewhat polar, while aliphatics are less so, hence aromatics tend to be more water soluble than aliphatic hydrocarbons. As with volatility, solubility generally declines with increasing molecular weight (AEHS 1998b).

Again, biodegradation rates are dependent on environmental conditions, including oxygen availability and the microbial population present, but they also depend on the susceptibility of the hydrocarbons. Generally, straight-chain alkanes degrade more quickly than branched alkanes or cycloalkanes (AEHS 1998a). The BTEX compounds tend to be more amenable to biodegradation than PAHs, and the potential for biodegradation of PAHs declines as the number of benzene rings in the chemical structure increases (AEHS 1998b).

The result of all of these weathering processes is that the more volatile, soluble, and degradable compounds will disappear most quickly, leaving behind the more persistent, recalcitrant compounds (AEHS 1998b), which include compounds of higher molecular weight and, in particular, larger PAHs, whose resistance to these processes comes from the stability imparted by the resonance structures of the benzene rings (AEHS 1998b; Kanaly 2000).

2.3. Risk Posed by Petroleum Hydrocarbons

Because there are so many individual constituents of petroleum hydrocarbons, it is difficult to determine the effect of each constituent within the context of a hydrocarbon mixture (AEHS 1997b); however, aromatic compounds tend to be more toxic than aliphatic compounds. A list was compiled in 1999 that prioritized chemicals based on the frequency of their occurrence at National Priorities List (NPL) sites and their risk to human health and the environment. On this list, PAHs collectively were ranked ninth, and benzo(a)pyrene was ranked eighth (Olson 2003). At least 54 PAHs have been identified at sites on the NPL (ATSDR 2004), and a number of PAHs have been determined to be probable human carcinogens. Of the other hydrocarbon constituents, benzene is also of concern because it has been determined to be a known human carcinogen (EPA 2006a).

Table 3 shows some of the hydrocarbon constituents that have been identified as known or probable human carcinogens.

Table 3.
Carcinogenicity of Selected Hydrocarbon Constituents

Chemical	Classification	Explanation
Benzene	A	Known Human Carcinogen
Benz[a]anthracene	B2	Probable Human Carcinogen
Benzo[b]fluoranthene	B2	Probable Human Carcinogen
Benzo[k]fluoranthene	B2	Probable Human Carcinogen
Benzo[a]pyrene	B2	Probable Human Carcinogen
Chrysene	B2	Probable Human Carcinogen
Dibenz[a,h]anthracene	B2	Probable Human Carcinogen
Indeno[1,2,3-c,d]pyrene	B2	Probable Human Carcinogen

Source: EPA (2006a).

Detailed toxicological profiles of gasoline, PAHs, and other hydrocarbons are available from the Agency for Toxic Substances and Disease Registry website at www.atsdr.cdc.gov/toxpro2.html#Final. The Association for Environmental Health and Sciences TPH Working Group also examined available toxicity studies for various petroleum hydrocarbon constituents and mixtures and also developed reference doses and reference concentrations for various hydrocarbon ranges. That work is available online at www.aehs.com/publications/catalog/contents/Volume4.pdf.

2.4. Application of Phytoremediation to Petroleum Hydrocarbons and PAHs

In general, uptake of hydrocarbons into plants, although possible, is not expected in great quantities given the compounds' chemical properties, including high molecular weights, relatively low solubilities in water, and hydrophobic nature (EPA 2000b; Hutchinson 2003).

As discussed in Section 2.2, microbial degradation of hydrocarbons is possible, even without engineered vegetation. And as discussed in Section 1.1, many times more microorganisms are generally found in the plant rhizosphere than in unplanted soil, which suggests that hydrocarbon degradation could be enhanced by the presence of vegetation (Hutchinson 2003). Numerous researchers have established that the primary mechanism for the disappearance of both petroleum hydrocarbons and PAHs is rhizodegradation (EPA 2000b; Hutchinson 2003). There is some indication that the presence of hydrocarbons may even encourage the proliferation of hydrocarbon-degrading microorganisms (Hutchinson 2003).

Although the biodegradation of both petroleum hydrocarbons and PAHs can proceed under either aerobic or anaerobic conditions, the degradation rates will be faster in the presence of oxygen. The presence of plants can help with oxygen availability either by transporting oxygen or by creating void spaces in the subsurface that allow for greater oxygen diffusion from the atmosphere (Tsao 2003).

As discussed in Section 2.2, all hydrocarbon constituents will not react in the same manner or degrade at the same rate. In general, smaller, less complex, or lower-molecular-weight hydrocarbons will be more readily degraded by microorganisms. This means that concentrations of straight chain alkanes might disappear before branched alkanes, which will disappear more quickly in phytoremediation than aromatic hydrocarbons, including PAHs (Elmendorf 1994).

Similarly, while low-molecular-weight PAHs are known to biodegrade under aerobic conditions, larger PAHs tend to be less amenable to biodegradation, making them more persistent in soil and groundwater (Olson 2003). Some researchers also believe that high-molecular-weight PAHs can degrade only cometabolically, that is, when lower-molecular-weight PAHs are present and can induce the production of enzymes required for PAH degradation (McCutcheon 2003; Olson 2003), which would become less likely as smaller PAHs degrade and are no longer present to participate in the cometabolic process. The persistence of larger (three rings or more) PAHs is also of concern because they may be more toxic or carcinogenic (Olson 2003) than the lighter PAHs.

Some authors have asserted that the persistence of larger PAHs or other constituents remaining in weathered hydrocarbons in the presence of hydrocarbon-degrading microbes and the necessary enzymes may be due to low bioavailability (Olson 2003; Kulakow 2000). Furthermore, hydrocarbons tend to sorb to soil or root surfaces or may be incorporated into the organic material, as in humification (Hutchinson 2003); humification is believed to further reduce the bioavailability of the incorporated compounds (McCutcheon 2003). Because the presence of vegetation can cause increased humification, thereby further reducing both the bioavailability and the mobility of these compounds, this process can be thought of as phytostabilization, even though concentrations of the compounds might not decline (McCutcheon 2003).

It should be noted that hydraulic control is also a feasible phytoremediation mechanism for control of groundwater contamination in particular, because the characteristics of the contaminants are not as relevant to the success of the technique.

3. DATABASE OF FIELD SITES

One of the primary motivations of this effort is to supplement the existing database currently supported by the Technology Innovation Program of EPA's Office of Superfund Remediation and Technology Innovation. The existing database is a result of work over the last several years to identify pilot studies, field-scale demonstrations, and full-scale phytoremediation projects, with particular focus on various contaminant groups, such as chlorinated solvents, metals, pesticides, or explosives (Green 2004). Although some of these sites have multiple contaminants that may include petroleum hydrocarbons, BTEX, or PAHs, no specific effort has focused on petroleum hydrocarbons to this point.

3.1. Process/Sources

In order to be useful to those interested in phytoremediation, this document is not limited to a handful of well-known sites but instead aims to be as comprehensive as possible in its depiction of the state of phytoremediation installation today.

Potential sites for inclusion in the database were identified from a variety of sources:

- Existing profiles in the CLUIN phytoremediation database (http://cluin.org/products/phyto/)
- Literature searches
- Solicitations of vendors and consultants known to have performed phytoremediation work
- Solicitations of petroleum industry contacts
- Solicitations of participants in the proposed phytoremediation society
- General Internet searches for relevant projects or research

When possible, information obtained from the existing CLUIN database, journal articles, or websites was sent to the corresponding author or primary contact to allow them the opportunity to update the information and ensure its accuracy.

3.2. Criteria for Inclusion

Because information compiled for this report may eventually be included in the CLUIN Database of Phytotechnology Project Profiles found at cluin.org/products/phyto/, information collected was formatted to blend with existing profiles.

Once sites at which phytoremediation had been implemented for remediation of hydrocarbon contamination were identified, they were included only if sufficient information could be obtained about the work. An effort was made to collect the following information on all identified sites; however, complete information was not available for all sites, although all available information is included.

- Site Name
- Site Location*
- Current/Former Uses of the Site
- Project Scale*
- Project Status
- Project Start Date*
- Project Completion Date
- Media Treated*
- Site Characterizations
- Contaminants*
- Initial Contaminant Concentrations
- Phytotechnology Mechanisms
- Vegetation Type*
- Planting Descriptions
- Acreage
- Evapotranspiration Rate
- Climate
- Operation/Maintenance Requirements
- Final Contaminant Concentrations
- Other Performance Data
- Cost
- Funding Source
- Lessons Learned
- Comments
- Primary Contact*
- Sources of Information

The starred parameters are considered minimal information requirements, without which sites were not included. Lab-scale projects and greenhouse studies were also not used.

3.3. Characteristics of Included Sites

The minimum information was collected for a total of 75 sites. The sites are located in 33 different states across the United States, including New England, the Southeast, the Midwest, and the West, as well as Hawaii and Alaska. Nine other countries are also represented:

- Australia
- Belgium
- Canada
- Denmark
- Finland
- Italy
- The Netherlands
- Russia
- United Kingdom

In addition to more traditional phytoremediation applications, the sites include diverse phytoremediation applications, such as constructed wetlands, field tests of phytotoxicity, investigations of natural revegetation, and an alternative landfill cover.

Table 4 summarizes the following preliminary information for each site:

- The year vegetation was planted at the site,
- The project scale,
- The media targeted by the project,
- The predominant contaminant or contaminant group at the site,
- The depth to contamination, and
- General vegetation descriptions.

This summary table should allow quick comparison of an existing site to one where phytoremediation has already been implemented and also points to more complete information for each of the projects in Appendix A.

Table 4

Summary of Phytoremediation Projects Detailed in Appendix A

				Scale			Media			Contaminants					Mechanism							Vegetation Type									
Page in Appendix A	Site	Location	Year Planted	Pilot-Scale or Field Demonstration	Full-Scale	Area (acres)	Soil	Groundwater	Other	BTEX	TPH	PAHs	Petroleum Predominant Contaminant?	Depth to Contamination (ft bgs)	Rhizodegradation	Phytodegradation	Hydraulic Control	Phytoextraction	Phytostabilization	Rhizofiltration	Phytovolatilization	Monoculture?	Poplar	Willows	Grasses	Legumes	Constructed Wetland	Irrigation?	Fertilization?	Cost Data?	Performance Data?
1		Butner, NC	2000		x	1	x	x		x			Y				x	x						x	x					Y	
2		Limon, CO	1995		x	<1		x			x		Y									x	x					Y		Y	
3		McCormick, SC	2001		x	4		x		x			Y				x	x					x	x	x					Y	
4		Tacoma, WA	1998		x	<1		x			x		Y									x	x					Y		Y	
5		Warren, OH	1997		x	1	x	x		x	x		Y				x	x				x	x							S	S
6	Abandoned Gasoline Station	Axelved, Denmark	1999	x		0.35	x				x		Y	0 - 10									x	x							Y
8	Active Retail Gas Station	Kenton, OH	1997		x	0.6		x		x			Y	2+	x		x	x			x		x	x				N	Y	Y	Y
10	Adjacent Gasoline Retail Outlets	Raleigh, NC	2003		x			x			x		Y	20			x						x	x				Y			
11	Amsterdam Terminal	Netherlands	2000		x	2 - 3		x				x	Y		x		x						x	x				Y	Y		
12	Argonne National Laboratory-East, 317/319 Area	Argonne, IL	1999		x	4	x	x		x			N	20 to 30		x	x		x				x	x	x	x			Y	Y	Y
16	Ashland, Inc. Facility	Milwaukee, WI	2000		x	0.4	x	x		x	x	x	N				x	x			x		x		x			Y	N	Y	Y
18	Atlas Tack Corp. Superfund Site	Fairhaven, MA	2007		x			x		x		x	N				x													Y	
19	Blockhouse Valley Landfill	Oak Ridge, TN	2005		x	15	x	x		x			N				x					x	x				x		Y	Y	
21	Bofors Nobel	Muskegon, MI	2002	x	x	50	x	x		x			N			x		x					x	x				Y	Y	Y	Y
23	Bus Depot	Tampere, Finland	2000	x		<1	x				x		Y		x								x		x	x					Y
25	Carteret Terminal	NJ	2000		x	<1		x		x			Y		x	x	x				x	x	x								
26	Charleston Manufactured Gas Plant	Charleston, SC	1998	x			x	x		x		x	Y	0 - 4+	x	x		x			x										
27	Combustion, Inc. Superfund Site	Denham Springs, LA	2001		x	3.7		x		x			Y	0 - 30		x	x						x	x				Y		Y	
30	Craney Island Fuel Terminal	Portsmouth, VA	1995	x		2.01	x				x		Y	0 - 1.5	x	x						x*			x	x		Y			Y
32	Crude Oil-Contaminated Wetland on the St. Lawrence River	Quebec, Canada	1999	x					Sediment		x		Y	Surface	x														Y		Y
34	Crude Oil Spill Site	Southeast TX	1994	x		<1	x				x		Y		x							x*			x				Y		Y

Table 4
Summary of Phytoremediation Projects Detailed in Appendix A

Page in Appendix A	Site	Location	Year Planted	Scale: Pilot-Scale or Field Demonstration	Scale: Full-Scale	Area (acres)	Media: Soil	Media: Groundwater	Media: Other	Contaminants: BTEX	Contaminants: TPH	Contaminants: PAHs	Contaminants: Petroleum Predominant Contaminant?	Depth to Contamination (ft bgs)	Mechanism: Rhizodegradation	Mechanism: Phytodegradation	Mechanism: Hydraulic Control	Mechanism: Phytoextraction	Mechanism: Phytostabilization	Mechanism: Rhizofiltration	Mechanism: Phytovolatilization	Vegetation Type: Monoculture?	Vegetation Type: Poplar	Vegetation Type: Willows	Vegetation Type: Grasses	Vegetation Type: Legumes	Vegetation Type: Constructed Wetland	Irrigation?	Fertilization?	Cost Data?	Performance Data?
36	Doraville Terminal	GA	1999		x	<1		x	Surface water		x		Y		x		x								x			Y	Y		
37	Edward Sears Property	New Gretna, NJ	1996	x			x	x		x			N	5 to 20		x	x					x	x					Y	Y	Y	Y
40	Experimental Dredged Sediment Disposal Sites	Menen, Belgium	1999	x		<1			Dredged sediment		x	x	Y	0 - 3	x							x		x							Y
42	Former Chevron Terminal	Ogden, UT	1996	x	x			x		x	x		Y	3+			x					x	x					N		Y	Y
44	Former Industrial Facility	Stratford, WI	1994		x	1	x				x		Y	3 - 8	x							x		x				Y	Y		S
45	Former Industrial Sludge Basin	Southeast TX	NA		x	1.1	x					x	Y	Surface	x										x			N	N		Y
47	Former John Rogers Tank Farm, Hickham AFB	HI	2000		x	1.1	x			x	x	x	Y		x													Y		Y	Y
49	Former Refinery	Casper, WY	2003		x	3 - 4			Extracted groundwater	x	x		Y		x	x								x			x				Y
51	Former Refinery and Tank Farm	Cabin Creek, WV	1999		x		x				x		Y										x		x						Q
52	Fort Wainwright	Fairbanks, AK	1997		x	<1	x					x	N	Surface		x		x				x		x				Y	Y		S
53	Gasoline Release	GA	1999	x	x		x	x		x			Y	0 - 5	x	x					x			x				Y	Y		Y
55	Grand Forks Air Base	Grand Forks, ND	2001	x		0.7	x	x			x		N			x	x						x					Y	N	Y	S
57	Greiner's Lagoon	Fremont, OH	2006		x	10	x	x		x			Y	1+			x						x		x					Y	Q
59	Hydrocarbon Burn Facility, NASA Kennedy Space Center	Cape Canaveral, FL	1998		x		x	x			x		Y	0 - 12		x	x						x		x			Y		Y	
60	Indiana Harbors Canal	Near Gary, IN	2002	x			x	x			x	x	Y	0 - 1									x	x							Y
62	Jones Island Confined Disposal Facility - Project 1	Milwaukee, WI	2001	x					Dredged sediment		x	x	Y	<1	x	x						x*		x				Y		Y	Y
64	Jones Island Confined Disposal Facility - Project 2	Milwaukee, WI	2002	x		<1			Dredged sediment			x	Y	Surface		x		x				x*		x	x			N	Y		Y
66	Krasnodar	Russia	2004		x	2 - 3	x					x	Y		x													Y	Y		
67	Kwinana Refinery	Western Australia	2000		x	1 - 2	x	x		x	x		Y		x		x					x						Y	Y		
68	LA Truck Depot	Lafayette, LA	1996		x		x	x			x		N	0 - 5				x			x		x	x				N	N		Y
69	Llandarcy Refinery	Wales, UK	2001	x		<1			Extracted groundwater		x		Y		x	x									x		x	Y?	Y		

Table 4
Summary of Phytoremediation Projects Detailed in Appendix A

				Scale			Media			Contaminants					Mechanism							Vegetation Type									
Page in Appendix A	Site	Location	Year Planted	Pilot-Scale or Field Demonstration	Full-Scale	Area (acres)	Soil	Groundwater	Other	BTEX	TPH	PAHs	Petroleum Predominant Contaminant?	Depth to Contamination (ft bgs)	Rhizodegradation	Phytodegradation	Hydraulic Control	Phytoextraction	Phytostabilization	Rhizofiltration	Phytovolatilization	Monoculture?	Poplar	Willows	Grasses	Legumes	Constructed Wetland	Irrigation?	Fertilization?	Cost Data?	Performance Data?
70	McCormick & Baxter Superfund Site	Portland, OR	1997		x	<1	x					x	Y		x	x							x		x			Y	Y	S	
71	Oil Well Blow Out Site	Trecate, Italy	1998	x		11	x				x	x	Y	Surface	x			x				x*			x	x					Y
73	Oneida Tie Yard Site	Oneida, TN	1997		x	2	x	x				x	Y	Surface	x						x	x	x							Y	Y
75	Oregon Pipleline	IL	2000		x	22	x			x			Y		x	x					x	x				x		Y	Y		
76	Phytoremediation Demonstration Plots at the Allen Park Clay Mine Landfill	Allen Park, MI	2001	x			x					x	Y		x										x						Y
78	Privately Owned Scrap Yard	Southeastern US	2001		x	2	x				x		Y	0 - 3											x			Y	Y		Y
79	Rochelle Terminal	IL	2003	x		<1		x		x			Y		x	x	x				x	x	x					Y	Y		
80	Rouge Manufacturing Complex	Dearborn, MI	2002		x		x					x	Y		x										x					Y	
81	RTDF Site A	Central CA	1998	x		<1	x				x	x	Y	0 - 12	x				x						x	x			Y		Y
83	RTDF Site B	Southwest OH	1999	x		<1	x				x	x	Y	2.5	x				x				x	x	x	x			Y		Y
85	RTDF Site C	Barrow, AK	1999	x		<1	x				x		Y	3 - 5	x	x			x						x	x			Y	Y	Y
88	RTDF Site D	Galena, AK	1998	x		<1	x			x	x	x	Y	3+	x	x			x						x	x			Y	Y	Y
91	RTDF Site E	Metlakatla, AK	1998	x		<1	x				x	x	Y	0 - 2	x	x			x						x	x			Y	Y	Y
94	RTDF Site F	Utica, NY	1999	x		<1	x				x	x	Y	20	x				x				x	x					N		Y
96	RTDF Site G	Fort Riley, KS	1999	x		<1	x				x	x	Y	2	x				x						x	x			Y		Y
98	RTDF Site H	Providence, RI	2001	x			x				x	x	Y	<15	x				x						x	x			y		Y
99	RTDF Site I	Southern IL	2000	x			x				x	x	Y	<2	x				x						x	x			Y		Y
100	RTDF Site J	El Dorado, AR	1999	x		<1	x				x	x	Y		x				x						x	x			Y		Y
101	RTDF Site K	IN	1999	x		<1	x				x	x	Y	2 - 6+	x				x				x	x					Y		Y
103	Solvent Spill Site	Central IA	2002		x	~1		x		x			N	11+									x		x						S
104	SRSNE Superfund Site	Southington, CT	1998	x			x	x		x			N	3 - 30+	x	x	x				x		x	x					Y	Y	Y
106	Sugar Creek Refinery Norledge	MO	2004		x	<1		x		x			Y		x	x	x				x		x					Y	Y		

Table 4
Summary of Phytoremediation Projects Detailed in Appendix A

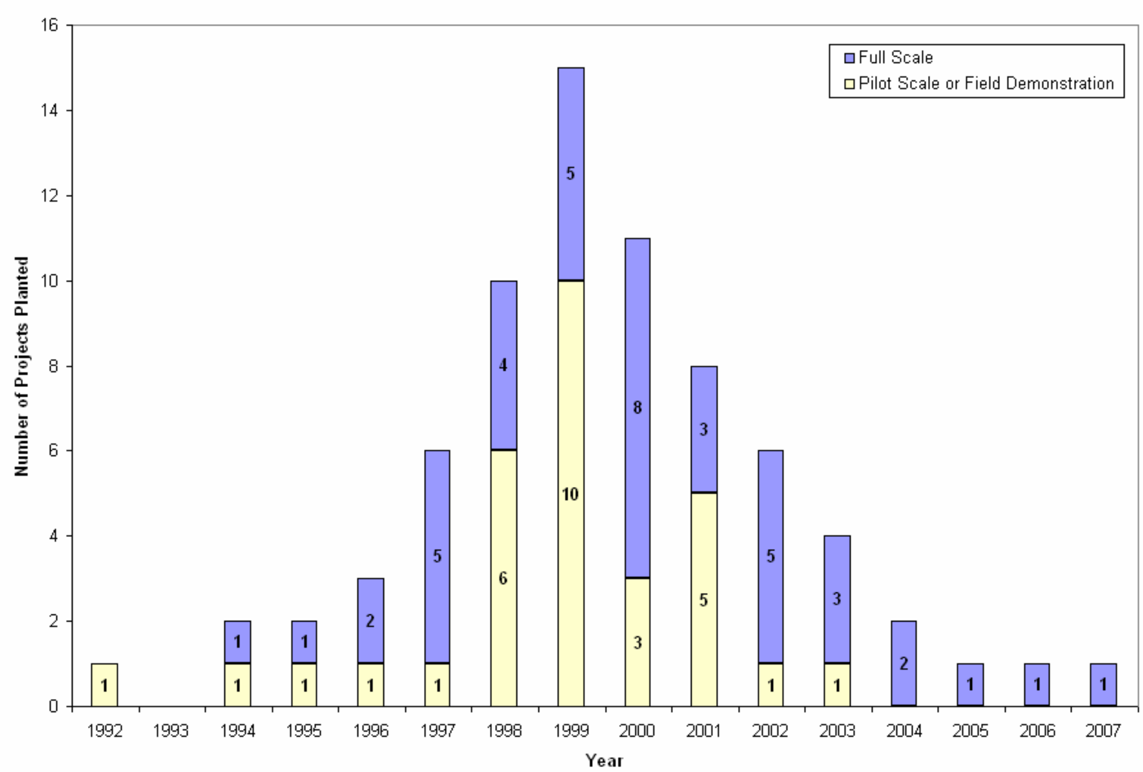
				Scale			Media			Contaminants					Mechanism							Vegetation Type									
Page in Appendix A	Site	Location	Year Planted	Pilot-Scale or Field Demonstration	Full-Scale	Area (acres)	Soil	Groundwater	Other	BTEX	TPH	PAHs	Petroleum Predominant Contaminant?	Depth to Contamination (ft bgs)	Rhizodegradation	Phytodegradation	Hydraulic Control	Phytoextraction	Phytostabilization	Rhizofiltration	Phytovolatilization	Monoculture?	Poplar	Willows	Grasses	Legumes	Constructed Wetland	Irrigation?	Fertilization?	Cost Data?	Performance Data?
107	Sugar Creek Refinery T156	MO	2002		x	<1		x		x			Y		x	x	x				x		x	x				Y	Y		
108	Texas City Chemicals A Plant	TX	2002		x	1 - 2		x				x	Y		x		x					x						Y	Y		
109	Texas City Refinery LTF	TX	1998		x	26	x				x	x	Y		x										x			Y	Y		
110	Tibbetts Road	Barrington, NH	1998		x	2	x	x		x			N			x	x						x		x					Y	S
111	Toluene- and TCE-contaminated Site	St. Augustine, FL	2000	x			x			x			Y			x															Y
113	Union Carbide Seadrift Plant	Seadrift, TX	1992	x		<1	x					x	Y	0 - 4	x							x*			x			N	Y		Y
115	Unknown Toluene-Contaminated Site	Moonachie, NJ	1997	x			x	x		x			Y			x					x	x	x							Y	S
117	Whiting Refinery 1st/126th St.	IN	1999		x		x				x		Y		x										x			Y	Y		
118	Whiting Refinery Cal Ave.	IN	2000		x		x	x		x			Y		x	x									x			Y	Y		
119	Wood River Refinery T293	IL	2003		x		x	x		x			Y		x	x					x				x			Y	Y		
120	Wood Treatment Facility	Central LA	1999	x		30	x	x				x	Y	0 - 40		x						x									

Monoculture? x* = More than one plant was tested, but individual plants were tested in different plots.
Cost Data? / Performance Data? S = Some or limited data. Q = Qualitative data only.

3.3.1. Timing and Scale of Projects

Of the 75 sites included in this report, 74 reported information on the year in which vegetation was planted at the site and the scale of the project. Figure 2 shows the number of phytoremediation projects planted in each year and the scale of each of the projects.

Figure 2.
Year of Planting and Scale of Projects



Considering that the term "phytoremediation" was coined in 1991, and 1994 was the first year that it was used in open literature, it is not surprising that there were only a handful of applications in the early 1990s. Similarly, because phytoremediation projects often require multiple growing seasons for tree stands or other vegetation to become fully established and to affect contaminant concentrations or groundwater flow, it is to be expected that few projects planted in the last two to three years would be reported.

Comparing the periods of 1995 to 1999 and 2000 to 2004 may show evidence of the maturing of the technology.

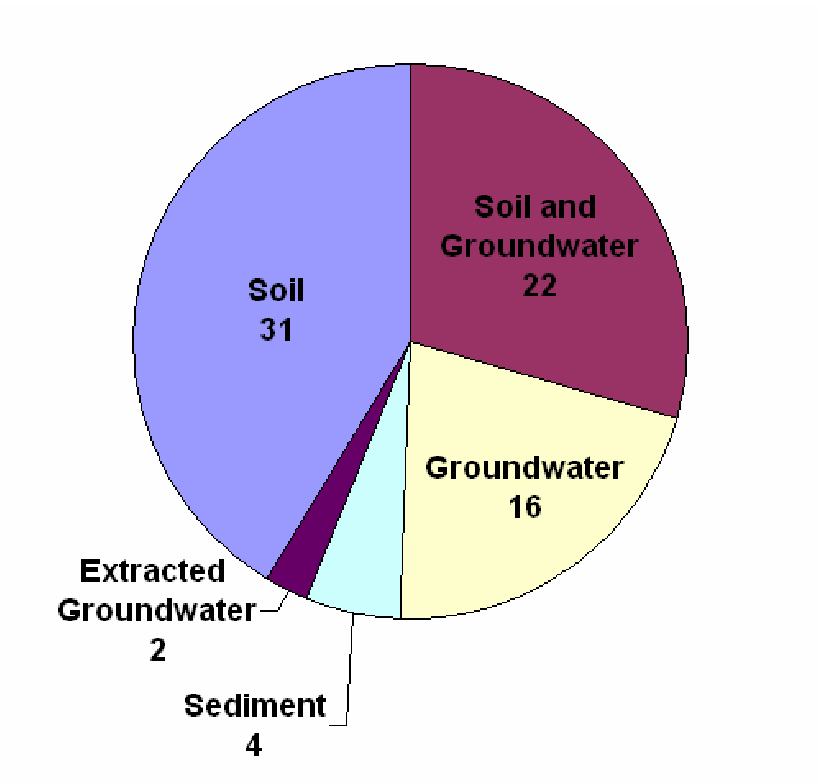
	Pilot-Scale and Field Demonstration Projects	Full-Scale Projects	Total Number of Projects Started
1995 – 1999	19	17	36
2000 – 2004	10	21	31

The total number of projects implemented in the last half of the 1990s is comparable to the total number of projects implemented in the first half of this decade; however, pilot-scale and field demonstration projects make up a smaller fraction of the overall number between 2000 and 2004. It should also be noted that the apparent spike in 1998 and 1999 can be attributed to the initiation of the Remediation Technologies Development Forum (RTDF) field trials, which were specifically intended to demonstrate the capabilities of phytoremediation of petroleum hydrocarbon contamination; nine of these trials were planted in 1998 and 1999.

3.3.2. Contaminated Media

As shown in Figure 3, more than forty percent of the 75 included sites are intended to address contaminated soil only, while nearly thirty percent address both soil and groundwater, and more than twenty percent address contaminated groundwater only. Only a handful of projects that target contaminated sediment or extracted groundwater were identified. Soil tends to be the targeted medium for phytoremediation of petroleum hydrocarbons because contaminant degradation generally occurs in the rhizosphere. Plant roots need to be able to reach the depth of contamination, which is possible in soil and shallow groundwater.

Figure 3.
Media Treated by Phytoremediation Projects



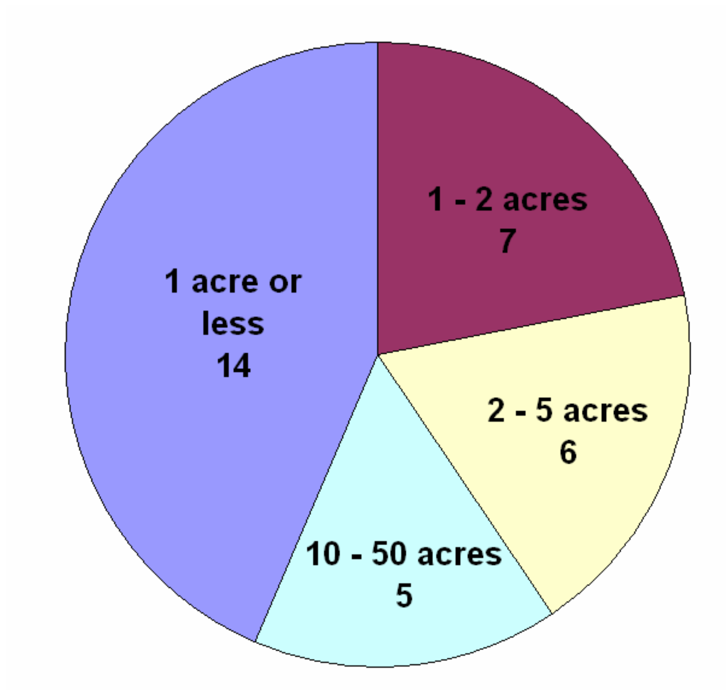
3.3.3. Predominant Contaminant

Since the petroleum hydrocarbons category of chemicals encompasses a large number of individual constituents, phytoremediation projects at these sites will often address mixtures of contaminants. Of the 75 sites identified in this report, 28 sites have chemicals of concern other than petroleum hydrocarbons, but the predominant chemicals of concern at 63 of the 75 sites are identified variously as TPH, diesel-range organics, gasoline-range organics, crude oil, PAHs, or one of the BTEX compounds.

3.3.4. Project Size

Of the 75 sites listed in Appendix A, information on the size of the project was available for 52 sites; 20 are pilot-scale or field-demonstration projects, while 32 are full-scale projects. Eighteen of the 20 pilot-scale or field-demonstration sites occupied less than one acre, but a limited size is to be expected during pilot testing and field demonstrations; however, it is worth noting that even among the 32 full-scale projects with project size information available, more than sixty percent of the projects occupy two acres or less, and less than twenty percent are 10 acres or larger, as shown in Figure 4.

Figure 4.
Size of Full-Scale Phytoremediation Projects



3.3.5. Phytoremediation Mechanisms

The mechanism used in a phytoremediation project largely depends on the contaminant of concern at the site. Of the 63 sites for which petroleum hydrocarbons are the predominant chemical of concern, information on the phytoremediation mechanism was available for 57 sites. Six of the seven mechanisms discussed in Section 1.1 (all except rhizofiltration) are cited at least once as the mechanism responsible for the disappearance of the hydrocarbon contaminant, but rhizodegradation is by far the most prevalent mechanism. Forty-five of the 57 sites for which this information was available are believed to be employing rhizodegradation, while phytodegradation was named as one of the mechanisms at 23 sites and hydraulic control at 17 sites.

Each of these mechanisms appears to have been employed steadily over the last 15 years, with rhizodegradation noted as early as 1992 and as recently as 2004, phytodegradation from 1995 through at least 2004, and hydraulic control from 1996 to a project begun in 2006.

The complexity of phytoremediation and the difficulty in identifying the exact mechanism at work is also worth noting: only 16 of the 57 sites indicate a single phytoremediation mechanism at work on the site.

3.3.6. Vegetation Types

Some information was available on the types of vegetation used for all 75 of the sites identified in this report. While pilot-scale projects or field demonstrations might test a variety of species, some full-scale installations use just one variety of vegetation, whereas others install a diverse habitat that more closely mimics natural vegetation. Of the 75 sites, 43 are full-scale projects. Of those 43 projects, only 12 of the sites have planted just a single species of vegetation. The monocultures were employed as early as 1994 and as recently as 2005. Of the 12 monoculture sites, seven have hybrid poplars, with the others using willows, legumes, or eucalyptus.

Although grasses are not employed as a monoculture at any of these sites, they are often used in conjunction with other species. As previously stated, some type of hydrocarbon constituent is the predominant contaminant at 63 of the 75 sites. Various grass species are employed at 31 of these 63 sites. Other commonly planted vegetation includes hybrid poplars at 25 of the 63 sites, followed by willows at 18 sites and legumes at 13 sites. The only other plants specifically identified at two or more of these full-scale sites are eucalyptus, maples, pines, mulberry trees, and wetland species like cattails, rush, and bulrushes.

Rhizodegradation is identified as the phytoremediation mechanism at a large number of the sites, and the same variety of vegetation is employed across these sites. Of the 17 sites discussed in Section 3.3.5 that identify hydraulic control as the mechanism at work, the phreatophytic hybrid poplars and/or willows are used at 15 of them, and of the 38 sites attempting to treat contaminated groundwater that are discussed in Section 3.3.2, 28 also employ hybrid poplars or willows.

3.4. Cost and Performance Data

As stated previously, the information compiled in this document was collected to allow others to evaluate phytoremediation projects in the future, and cost and performance data are crucial to that evaluation.

3.4.1. Example Cost Data

Of the 75 total sites included in Appendix A, some indication of project cost was provided for 28 of the sites. Only a very few projects had thorough information on design, installation, and operation and maintenance costs, and costs vary widely even on comparably sized sites, as shown in Table 5.

Table 5.
Example Cost Data

Site	Area	Design Cost	Installation Cost	Annual Operation and Maintenance Cost
RTDF Sites C, D, & E (Alaska)	<1 acre	NA	$7,250	$7,400
Oneida Tie Yard Site (Oneida, TN)	2 acres	$50,000	$90,000	$20,000
Butner, NC	1 acre	$7,600	$30,400	$5,000
Active Retail Gas Station (Kenton, OH)	1 acre	$3,500	$12,000	$8,500
McCormick, SC	4 acres	$10,000	$35,000	$15,000
Combustion, Inc. Superfund Site (Denham Springs, LA)	3.7 acres	NA	$654,000	$78,400

3.4.2. Available Performance Data

As discussed in Section 3.3.3, 63 of the 75 sites have a petroleum constituent as the predominant contaminant. Of these 63 sites, some performance data, either qualitative or quantitative, were provided for 33 of the sites. Thirty of these 33 sites have contaminant concentration data, with 26 of the sites seeing a decline in concentrations. Reductions in contaminant concentrations vary among sites and also among contaminant groups. A nearly 100% reduction of TPH concentrations was realized at a privately owned scrap yard in the southeastern United States, while a gasoline spill site in Georgia saw almost an 80 percent decrease in BTEX concentrations in soil, and PAH concentrations declined more than 60 percent on some of the phytoremediation demonstration plots at the Allen Park Clay Mine Landfill.

It should also be pointed out that because petroleum hydrocarbons undergo weathering processes, a decline in hydrocarbon concentrations even in the absence of vegetation would not be unexpected. Of the 30 sites that provided some contaminant concentration data, 20 sites also had an unvegetated control plot. Of these 20 sites, nine sites showed a significantly greater contaminant decline in the vegetated plots than in the unvegetated controls.

Three sites also offered evidence of the success of hydraulic control efforts.

3.4.3. Challenges of Promoting Phytoremediation

The most glaring shortcoming of the information compiled in this report is the lack of comprehensive cost and performance data on all of the included sites. This deficiency remains, even though particular emphasis was placed on obtaining cost and performance data for each site.

In March 2000, EPA published a report entitled *An Analysis of Barriers to Innovative Treatment Technologies: Summary of Existing Studies and Current Initiatives* (2000a). The report reviewed 10 previously published reports that identified barriers encountered in the attempt to gain acceptance for innovative remediation technologies. Although a total of 42 individual barriers were identified in the 10 reports, only four were mentioned by at least four of five authors. One of those four was that "[c]ost and performance data for specific ITTs [innovative treatment technologies] are limited" (EPA 2000a).

Out of the total of 75 sites included in this report, six are federal Superfund sites, and at least seven more are federally owned facilities (usually by DOE or the Department of Defense). These sites appear to play an important role in the establishment and acceptance of innovative technologies because they may be funded by research budgets where there is no shareholder demand for direct return on investment. Additionally, there may be more willingness—or even desire—to take a risk on something as yet unproven; however, for the remediation technology to flourish as time progresses, its use has to spread beyond federally owned or funded sites, and industry remediation experts and consultants must also come to include it among feasible, effective, and cost-effective remedial options.

The 2000 EPA report does identify government initiatives, including EPA's Superfund Innovative Technology Evaluation (SITE) program, that address barriers such as the lack of reliable cost and performance data. The SITE program is intended to "encourage…the development and implementation of innovative treatment technologies for hazardous waste site remediation" by implementing the technology at field sites and collecting data that would allow others to evaluate the potential for the technology to be implemented at other sites (EPA 2006b). Three of the projects listed in this report (Former Chevron Terminal in Ogden, UT; Argonne National Laboratory in Argonne, IL; and Jones Island Confined Disposal Facility) are SITE demonstration projects.

Another important component of the process of promoting phytoremediation has been the RTDF, which is intended to "foster collaboration between the public and private sectors in developing innovative solutions to mutual hazardous waste problems" (RTDF 2006). One of the RTDF groups established focused on phytoremediation of organic compounds, and later a subgroup focused specifically on phytoremediation of petroleum hydrocarbons. This subgroup led the RTDF field trials (see p. A-87 through A-109) that implemented and monitored phytoremediation of petroleum hydrocarbons at 11 sites across North America. These sites alone account for 14 percent of the sites included in this report and have likely had an important impact on the establishment of phytoremediation as a demonstrated remediation technology.

As the technology matures and the knowledge and experience in phytoremediation moves away from academic researchers and government agencies, it signals progress for the technology;

however, it may become more difficult to obtain cost and performance data as private industry and consultants (or their clients) have little incentive to share information about their sites.

The result is that phytoremediation has not reached the point at which its efficacy and cost advantages are universally accepted, but it has already grown beyond the period in which government organizations may be willing to support its use for demonstration purposes. A small number of installers and consulting firms and even larger companies have adopted the technology, but these private companies may be less forthcoming with costs and performance data, and it may therefore be increasingly challenging to continue the growth of phytoremediation.

4. CONSIDERATIONS FOR PHYTOREMEDIATION APPLICATION

The more detailed site descriptions and performance data available for these sites illustrate some of the important issues that have emerged in phytoremediation projects undertaken to address petroleum hydrocarbon contamination.

4.1. Contaminant Considerations

Contaminant characteristics will dictate in part what kinds of plants are used, what phytoremediation mechanisms are employed, and ultimately how successful the phytoremediation project is. Although the nature of contamination cannot be controlled or chosen like the type of vegetation used, a thorough characterization and understanding of the contamination is important.

4.1.1. Mixtures of Contaminants

As noted in Section 3.3.3, many sites with petroleum hydrocarbon contamination have other contaminants that may also require remediation. This complication may make it challenging to identify plant species to address all contaminants at a site. At one site (the privately owned scrap yard in the Southeastern United States), soil was contaminated with both TPH and PCBs. Attempting phytoremediation at this site required a mixture of both Bermuda grass (intended to address TPH) and mulberry trees. Appropriate planting density, timing, irrigation, and fertilization to achieve optimal growth of both plant types was not accomplished on the first attempt, but in the third growing season, petroleum hydrocarbon concentrations had declined from up to 14,800 milligrams per kilogram (mg/kg) to below detection limits, and the concentrations of PCBs declined from more than 200 mg/kg down to no more than 8.5 mg/kg (Hurt 2005). Another example of the complicated nature of using phytoremediation to address sites containing mixed contaminants can be seen at the bus depot in Tampere, Finland. In addition to petroleum hydrocarbons, the soil used for a field plot in that study also contained elevated levels of lead, copper, and zinc (Palmroth 2006a). It was not known whether the presence of the metals would inhibit the activity of hydrocarbon degraders in the subsurface. Hydrocarbon concentrations did decline substantially with no indication of an inhibitory effect, but there was also no evidence of phytoextraction of the metals (Palmroth 2006b).

4.1.2. Contaminant Depth

Contaminant depth is of obvious importance when phytoremediation is dependent upon microbial degradation of contaminants in the plant rhizosphere, as is often the case in the phytoremediation of petroleum hydrocarbons. Of the 34 sites for which information on the depth of contamination was provided, 30 sites indicated that contamination was encountered in the uppermost five feet at the site (although contamination may continue on deeper in many cases). Three of the other four sites that indicated contamination could be found at 10 feet or deeper are being used to address groundwater contamination. Efforts have been made in some cases to plant vegetation with roots at a specific depth of interest, either to target a particular zone of contamination or to encourage deep rooting, so that the trees would rely on groundwater as their source of water instead of surface or irrigation water. This method is known to have been used at at least six different sites (Argonne National Laboratory in Argonne, IL; a former industrial facility in Stratford, WI; a site in Limon, CO; an unknown toluene-contaminated site in Moonachie, NJ; the former Chevron Terminal in Ogden, UT; and adjacent retail gas outlets in Raleigh, NC). This approach was employed as early as 1994 and as recently as 2003.

4.1.3. Weathering of Hydrocarbons

As discussed in Section 2.2, even without the presence of an engineered phytoremediation system in place, hydrocarbon contamination will be susceptible to natural weathering effects, including leaching, evaporation, and even biodegradation. If hydrocarbon contamination has had substantial time to undergo weathering processes prior to the onset of phytoremediation, the potential for phytoremediation to cause substantial further decline in the contaminant concentrations may be diminished (AEHS 1998a).

It is also worth noting that the weathering processes would cause a decline in hydrocarbon concentrations even if vegetation is not installed. Phytoremediation may accelerate the decline, but the eventual endpoint reached in terms of hydrocarbon degradation might be comparable whether or not phytoremediation is implemented (EPA 2000b). For this reason, an unvegetated control plot is often part of a phytoremediation field demonstration to compare against the planted areas.

The RTDF field trials tested the ability of vegetation to reduce concentrations of hydrocarbons in soil at 11 sites of differing contaminant concentrations in varied soil types and climates, and each of these field demonstrations included an unvegetated control plot for comparison purposes. Furthermore, ratios of PAH concentrations in the control plots that, based on their chemical properties, differ in their susceptibility to microbial degradation were calculated and monitored through the course of the project to evaluate weathering processes. One of the results of that work is the conclusion that the age and weathering of the contaminants prior to the initiation of phytoremediation is important. Only two of the 11 sites saw significantly greater decline in hydrocarbon concentrations in the vegetated plot than in the unvegetated plot. At Site G, the medium being remediated was sediment recently excavated from a lagoon, and at site J, the contamination had resulted from an oil spill two years prior to planting. Researchers concluded that in both cases the limited weathering experienced prior to the initiation of phytoremediation allowed for phytoremediation to have a substantial, measurable effect on the soil hydrocarbon concentrations (Kulakow 2006).

Dr. Peter Kulakow, a researcher associated with the 11 RTDF field trials, has indicated that although a definite effect could not be established at the other nine sites, the vegetation might instead be having a phytostabilizing effect (personal communication 2006). The recalcitrance of the remaining compounds may indicate that they are not bioavailable, which would make further degradation success unlikely but also could diminish the risk that the contaminants pose for ecological and human exposures. Additional testing for plant uptake, bioavailability, and toxicity of the weathered hydrocarbons may be necessary to solidify this assertion.

4.1.4. Larger PAHs

The relative recalcitrance and toxicity of PAHs and the lack of attractive remedial alternatives has fueled great interest in the potential of rhizodegradation and other phytoremediation mechanisms to address PAH contamination in soil. Although some sites saw substantial reductions in both TPH and PAH concentrations, work at the Oneida Tie Yard Site in Oneida, TN, has documented that the reductions seen in PAH concentrations were due to the degradation largely of naphthalene and other three-ringed PAHs. These PAHs are known to be amenable to biodegradation, while the larger and often more toxic PAHs remain unaffected. Greater understanding of the potential for phytoremediation of these larger PAHs is needed.

4.2. Considerations in Plant Selection

Different plant species have been used repeatedly and successfully for phytoremediation of petroleum hydrocarbons; however, selection of appropriate vegetation is dependent upon different variables, such as climate, soil, the root system of the plant, and the plant's ability to survive the contamination (Neder 2004). Plant selection may also depend on the project goal: grasses and legumes have extensive root systems that may work well for rhizodegradation of hydrocarbons in shallow soil (Neder 2004), while phreatophytes like the hybrid poplars or willows can be used when the objective of the project is to alter groundwater flow and contaminant migration by transpiring as much water as possible.

4.2.1. Natural Revegetation

The work at the industrial sludge basin in Southwest Texas investigated the natural revegetation of land after petroleum hydrocarbon contamination has occurred. Researchers concluded that at least early on the in the remediation phase, plant selection is dependent on the ability of the plants to survive in the contaminated soil (Olson 2001), which is discussed further in Section 4.2.2. The survival of the pioneer species may affect contaminant concentrations and the soil environment enough to allow other species to flourish; the sludge basin project documented a progression from grasses and herbs eventually giving way to trees (Olson 2001). If engineered phytoremediation systems are to mimic natural systems, the use of multiple plant species is preferable and may need to be timed to mimic the succession process (Olson 2003).

Also, although plant survival and efficacy are crucial to the success of a phytoremediation project, this project points out that careful consideration should be given to the introduction and use of exotic plant species in phytoremediation projects. Native plants may be better able to survive in local climate or soil conditions and do not pose the same risk that non-native vegetation may present of unintended effects on the ecosystem (Neder 2004).

4.2.2. Phytotoxicity

As in the natural systems, vegetation in an engineered phytoremediation project must be able to survive in the contaminated soil for the technology to be effective. Although it is difficult to identify a precise concentration at which each petroleum constituent becomes toxic to vegetation, work done at an abandoned gasoline station in Axelved, Denmark, attempted to investigate the phytotoxic effects of diesel and gasoline on both willows and poplars (two of the most commonly used plant types, as discussed in Section 3.3.6) in the field. Work performed in the lab with soil taken from the gas station found that total hydrocarbon concentrations (of hydrocarbons between 5 and 28 carbons in length) of 810 mg/kg reduced transpiration by 10 percent, and a hydrocarbon concentration of 3,910 mg/kg reduced transpiration by 50 percent. Verification work with artificially contaminated soils found that gasoline was significantly more toxic to the tree species than diesel, but weathered gasoline was less toxic than fresh gasoline. Confirmation of these results in the field showed that the vegetation exhibited signs of stress (including the death of some planted trees), but no clear correlation existed between tree survival and concentrations of hydrocarbons in soil (Trapp 2001). The RTDF field trials saw a standard grass and legume mixture planted at sites across North America, as well as local vegetation chosen for each site. One of the key lessons identified at the conclusion of these trials was the ability of grass and legume species and other plants, including willows and poplars, to grow in hydrocarbon-contaminated soil where average TPH concentrations were as high as 40,000 mg/kg (Kulakow 2006).

4.3. Operation and Maintenance Considerations

Once plants are selected and planted, further care of vegetation is often needed. Operation and maintenance requirements vary from site to site and may vary as a tree stand or other vegetation matures. These activities can include fertilization, irrigation, mowing, weeding, pruning, replanting or replacing vegetation that does not survive, inspection of plants for growth and health, and sampling of soil and groundwater to detect changes in contaminant concentrations.

4.3.1. Fertilization

Of the 75 total sites, information was provided about nutrient addition at 46 of the sites, with 41 indicating that fertilization had been a part of the site maintenance work.

Fertilization can be essential for two reasons in the phytoremediation of petroleum hydrocarbons. First, contaminated soil may not have the necessary balance of minerals and other nutrients to allow the desired vegetation to grow adequately. Furthermore, the success of phytoremediation at these sites is often attributed to microbial degradation, and the microbial populations will also exert demand on nutrients in the soil (Hutchinson 2003).

The field demonstration at the bus depot in Tampere, Finland, did not achieve a significant decline in TPH concentrations in an unfertilized vegetated plot, while three fertilized plots (two with biosolids and one with a nitrogen, phosphorus, and potassium fertilizer) achieved more than a 60 percent reduction in TPH concentrations (Palmroth 2006b). Work at the Jones Island Confined Disposal Facility in Milwaukee, WI, compared the effect of various plant species on PAH concentrations and saw the greatest reduction in the treatments with less plant biomass, which the researchers attribute to the competition between the plant and the microbes for nutrients, indicating that nutrient availability does limit rhizodegradation. The effect, however, is not universal, as no benefit was seen from nutrient addition at a crude-oil contaminated freshwater wetland on the St. Lawrence River in Canada (Venosa 2002).

Where nutrient addition is deemed necessary, residuals from wastewater treatment plants and confined animal feeding operations and other biosolids may provide an excellent source of fertilizer, thereby avoiding landfill disposal of a reusable material.

4.3.2. Irrigation

Of the 75 total sites, information about irrigation was provided for 38 of the sites, with 32 indicating that irrigation was performed periodically as part of the site maintenance.

As with fertilization, irrigation may be required because water is essential to both plant and microbe growth (Hutchinson 2003). Although many sites did not indicate the method of irrigation used, at least four sites (Combustion, Inc., Superfund Site in Denham Springs, LA; Argonne National Lab in Argonne, IL; adjacent retail gasoline outlets in Raleigh, NC; and the former John Rogers Tank Farm at Hickham AFB in Hawaii) had dedicated irrigation systems installed. The Raleigh project was unique within this group in that irrigation was provided by a vertical subsurface drip system, which was intended to aid in the cultivation of deep-rooted plants. No universal approach to irrigation is successful. The project in Hawaii noted greater success with drip irrigation as opposed to spray irrigation, while the drip irrigation system at Combustion, Inc., was believed to encourage shallow rooting, which was not the desired effect. Furthermore, at sites where hydraulic control is the objective of the phytoremediation project, irrigation may be counterproductive in that a greater volume of irrigation water infiltrating the subsurface may reduce the amount of groundwater that the plants can transpire.

If groundwater is to be treated by the phytoremediation project, and irrigation is deemed necessary at the site, it may be possible to pump contaminated groundwater from the subsurface and use that water for irrigation. This strategy, which could both treat the contaminated groundwater and encourage plant growth, has been employed at the Del Monte Oahu Plantation Superfund Site in Kunia, HI, although not for treatment of petroleum hydrocarbons (EPA 2003b).

4.3.3. Aeration

As discussed in Section 2.4, microbial degradation of petroleum hydrocarbons and PAHs proceeds most quickly and favorably in the presence of oxygen. The importance of oxygen to the biodegradation of petroleum hydrocarbons in the subsurface was noted by researchers at the Jones Island Confined Disposal Facility in Milwaukee, WI. At Jones Island, dredged sediment was moved into a treatment cell for the field demonstration and thus moved from likely anaerobic conditions to a more aerated environment. Large declines in PAH concentrations were seen across a variety of treatments, including in cells with no vegetation at all, which the researchers believed was likely due to the advantage of aeration. Although vegetation is believed to aid in oxygen transport on its own, some phytoremediation projects do have features that aim to enhance subsurface aeration. When poplar trees were initially planted at the former Chevron terminal in Ogden, UT, PVC pipe was also placed in the borehole with the tree as a direct conduit for atmospheric oxygen.

4.3.4. Plant Harvesting

Some phytoremediation applications raise concerns about the ecological exposure that is possible when contaminants accumulate in plant biomass aboveground and the plants therefore require harvesting and disposal; however, uptake and accumulation of hydrocarbons by plants is not generally expected, and only one project (the Jones Confined Disposal Facility in Milwaukee, WI) indicated that the plants were harvested.

4.4. Consideration of Ecosystem Services

One final consideration should be the evaluation of phytoremediation in the context of "ecosystem services." When remedial options are being evaluated, the ecosystem services offered by each option should be determined and the option with the highest net environmental benefit chosen for implementation. Phytoremediation may be able to offer ecosystem services that traditional options like soil excavation do not. Carbon sequestration was offered in Section 1.2.3 as an example of a regulating service that phytoremediation offers, and it is possible to estimate the amount of carbon sequestered during the lifetime of a project. As an example, 300 willow trees were planted at the industrial facility in Wisconsin. At the time of planting, the trees were approximately three-quarters of an inch in breast-height diameter, but three growing seasons later the trees had grown to approximately four inches in diameter (Carman 2000). A database compiled by the U.S. Department of Agriculture includes equations that allow for the calculation of total plant biomass for willow trees based on breast-height diameter (USDA 2003). Assuming that carbon is half of the total biomass (Nowak 2002), these 300 trees are estimated to have stored almost 8,000 pounds of carbon since they were planted. The project covers approximately one acre, and given growth over the course of three years, the rate of carbon sequestration at this project is approximately 1.3 tons of carbon per acre per year, which is comparable to the national value of 0.94 tons of carbon per acre per year (as discussed in Section 1.2.3).

5. CONCLUSIONS

Seventy-five sites were identified at which phytoremediation has been implemented for pilot-scale, field-demonstration, or full-scale cleanup of petroleum hydrocarbon contamination. Information on the location, scale, start date, media treated, contaminants, vegetation type, and a primary contact was obtained for each site. These details and other available information are summarized in Appendix A. The sites are located in 33 different states across the United States, as well as in nine other countries.

The first of these projects was initiated in 1992, while planting on another is planned for 2007. The work appears to be trending from pilot- and field-scale projects to full-scale applications. More than 40 percent of the projects are intended to address only contaminated soil, while another 30 percent are treating both contaminated soil and groundwater. There are other projects in which phytoremediation is addressing contaminated groundwater in situ, extracted groundwater, and sediment.

Petroleum hydrocarbons are the primary contaminant at almost 85 percent of these sites, but more than 35 percent of the sites have additional contaminants. The sites where phytoremediation is installed for cleanup of petroleum hydrocarbons tend to be small, with more than 60 percent of the full-scale projects reportedly two acres or less.

Phytoextraction, phytovolatilization, phytodegradation, rhizodegradation, phytostabilization, and hydraulic control were each identified at least once as the phytoremediation mechanism at work in the project sites. Multiple mechanisms were indicated at most sites, with rhizodegradation the mechanism most frequently cited. Phytodegradation and hydraulic control were also noted at a fraction of the sites.

Grass is the most commonly planted type of vegetation among the sites, followed by hybrid poplars, willows, and legumes. More than 70 percent of full-scale sites involve a diverse culture of vegetation. Most sites with the objective of hydraulic control and/or groundwater cleanup employ hybrid poplars or willows.

Cost and performance data proved challenging to compile for many of these sites. Cost data were available for less than 40 percent of these sites. Costs varied widely even among the sites for which thorough cost data were available. Design cost ranged from $3,500 for a one-acre site to $50,000 for a two-acre site. Installation cost ranged from $7,250 each for three sites (each less than one acre) to $654,000 for a Superfund site of 3.7 acres. Annual operation and maintenance costs were as low as $5,000 for a one-acre site and up to $78,400 for the same 3.7-acre Superfund site.

Performance data were provided for just over half of the sites for which petroleum hydrocarbon was the primary contaminant. Nearly 80 percent of the sites saw a decline in contaminant concentrations; however, at sites that also maintained an unvegetated control plot for comparison purposes, fewer than half found a significant difference between the unvegetated and vegetated plots. Three sites did offer evidence of the success of hydraulic control efforts. The tracking of cost and performance data for phytoremediation projects may become more challenging as the technology matures, and more work is performed by private industry for cleanup rather than for research and demonstration purposes.

If phytoremediation is being considered as a part of the remedy at a petroleum hydrocarbon-contaminated site, its success will rely on thorough characterization and understanding of the contamination at the site. Although some success has been demonstrated, mixtures of contaminants make the phytoremediation design and selection more challenging. Depth of contamination is also important. Among petroleum hydrocarbon sites, contamination depth has typically been less than five feet bgs, but some effort has been made to direct roots to particular depths of contamination or to the groundwater. The amount of weathering that the hydrocarbons have undergone prior to the start of phytoremediation is also emerging as an important site characteristic. Weathered hydrocarbons appear to be more resistant to rhizodegradation, and the vegetation may have a phytostabilization effect instead of breaking down the contaminants. Similarly, larger PAHs continue to present a challenge in their recalcitrance, and more research will be required to develop effective phytoremediation techniques.

Once phytoremediation has been selected for a site, important decisions must be made in plant selection. First, investigation of natural vegetation encourages the use of diverse stands of vegetation as well as plant species that are native to the project area. It is also important that the vegetation is able to survive in the contaminated soil. One notable result of many of the projects included in this report is that various species of vegetation survived and grew in TPH concentrations of more than 40,000 mg/kg, which is substantially higher than laboratory research indicated might be feasible. Once vegetation has been planted, operation and maintenance is a crucial element of the successful application of phytoremediation to petroleum hydrocarbon sites. Although the need varies between locations, fertilization, irrigation, aeration, and harvesting should be considered. Fertilization and irrigation were often performed on the projects in Appendix A, but aeration and harvesting were not.

Lastly, when remedial options are being evaluated, it is important that consideration be given to all of the environmental benefits of phytoremediation beyond the realization of remedial goals. In addition to aesthetic improvements, air and water quality benefits, reduction of erosion, and shading that a phytoremediation project may provide, vegetation also has the ability to store carbon, thereby offsetting greenhouse gas emissions at a rate of one ton of carbon per acre per year or more. If eventual reuse of the site is contemplated and ecosystem services are identified and quantified, phytoremediation may be better integrated into that reuse.

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APPENDIX A

DETAILED INFORMATION ON PHYTOREMEDIATION FOR CLEANUP OF PETROLEUM HYDROCARBONS

Phytoremediation of Petroleum Hydrocarbons

Site Name	
Site Location	Butner, NC
Project Scale	
Project Status	Ongoing
Project Start Date	2000
Project Completion Date	
Media Treated	Soil, Groundwater
Site History and Background	
Site Characterizations	
Contaminants	BTEX, 2-Butanone, Methyl Isobutyl Ketone, Tetrahydrofuran
Initial Contaminant Concentrations	
Phytotechnology Mechanisms	Hydraulic control, phytoextraction
Vegetation Type	Hybrid poplars, Black Willows, Maples
Planting Descriptions	
Acreage	1 acre
Evapotranspiration Rates	
Climate	Temperature Range: -9 to 105F; Elevation: 443 ft; Mean annual precipitation: 41.4"; Growing season: 4/29-10/16
Operation/Maintenance Requirements	
Final Contaminant Concentrations	
Other Performance Data	
Cost	Design - $7,600 Installation - $30,400 Annual operations and maintenance - $5,000
Funding Source	
Lessons Learned	
Comments	
Primary Contact	Wojciech Jozewicz, ARCADIS, WJozewicz@arcadis-us.com
Sources of Information	Email from Wojciech Jozewicz to Ellen Rubin, 29 June 2006.

Phytoremediation of Petroleum Hydrocarbons

Site Name	
Site Location	Limon, Colorado
Project Scale	Full Scale
Project Status	Ongoing
Project Start Date	
Project Completion Date	
Media Treated	Groundwater
Site History and Background	Site was a gasoline service station and petroleum storage facility.
Site Characterizations	Groundwater is approximately 8 feet below ground surface.
Contaminants	Petroleum hydrocarbons
Initial Contaminant Concentrations	TPH - 1000 milligrams per liter (mg/L)
Phytotechnology Mechanisms	
Vegetation Type	Poplars
Planting Descriptions	Double rows of deep-rooted poplars (120 trees) were planted along the property line, to intersect a plume of TPH-contaminated groundwater. Tree spacing: 6 feet between trees, and 6 feet between rows.
Acreage	2400 square feet
Evapotranspiration Rates	
Climate	Temperature Range: -25- to 103F; Elevation: 5,333 ft; Mean annual precipitation: 15.4"; Growing season: 5/20-9/20
Operation/Maintenance Requirements	
Final Contaminant Concentrations	
Other Performance Data	
Cost	Cost of site preparation, planting, irrigation system, and maintenance (not analytical) - $30,000
Funding Source	
Lessons Learned	
Comments	
Primary Contact	Ari M. Ferro, Ph.D., Principal Technical Specialist, Phytoremediation, ENSR, (919) 872-6600, aferro@ensr.aecom.com
Sources of Information	www.epareachit.org

Phytoremediation of Petroleum Hydrocarbons

Site Name	
Site Location	McCormick, SC
Project Scale	
Project Status	Ongoing
Project Start Date	2001
Project Completion Date	
Media Treated	Groundwater
Site History and Background	
Site Characterizations	
Contaminants	Toluene, ethylbenzene, xylenes
Initial Contaminant Concentrations	
Phytotechnology Mechanisms	Hydraulic control, phytoextraction
Vegetation Type	Bermuda, hybrid poplars, black willows
Planting Descriptions	
Acreage	4 acres
Evapotranspiration Rates	
Climate	Temperature Range: -1- to 108F; Elevation: 134 ft; Mean annual precipitation: 44.6"; Growing season: 4/15-10/23
Operation/Maintenance Requirements	
Final Contaminant Concentrations	
Other Performance Data	
Cost	Design - $10,000 Installation - $35,000 Annual operations and maintenance - $15,000
Funding Source	
Lessons Learned	
Comments	Currently in long term operations, maintenance, and monitoring.
Primary Contact	Wojciech Jozewicz, ARCADIS, WJozewicz@arcadis-us.com
Sources of Information	Email from Wojciech Jozewicz to Ellen Rubin, 29 June 2006.

Phytoremediation of Petroleum Hydrocarbons

Site Name	
Site Location	Tacoma, WA
Project Scale	Full Scale
Project Status	Ongoing
Project Start Date	
Project Completion Date	
Media Treated	
Site History and Background	Site was a gasoline service station and petroleum storage facility.
Site Characterizations	
Contaminants	Petroleum hydrocarbons
Initial Contaminant Concentrations	
Phytotechnology Mechanisms	
Vegetation Type	Poplars
Planting Descriptions	A triple row of poplars (570 trees) was planted along the property line with the objective of intersecting a plume of TPH-contaminated groundwater. Tree spacing: 4-feet between trees; 6-feet between rows.
Acreage	18,750 square feet
Evapotranspiration Rates	
Climate	Temperature Range: 9 to 96F; Elevation: 125 ft; Mean annual precipitation 37.1"; Growing season: 4/20-10/27
Operation/Maintenance Requirements	
Final Contaminant Concentrations	
Other Performance Data	
Cost	Cost of site preparation, planting, irrigation system, and maintenance (not analytical) - $ 36,000
Funding Source	
Lessons Learned	
Comments	
Primary Contact	Ari M. Ferro, Ph.D., Principal Technical Specialist, Phytoremediation, ENSR, (919) 872-6600, aferro@ensr.aecom.com
Sources of Information	www.epareachit.org

Phytoremediation of Petroleum Hydrocarbons

Site Name	
Site Location	Warren, OH
Project Scale	
Project Status	Ongoing
Project Start Date	1997
Project Completion Date	
Media Treated	Soil, groundwater
Site History and Background	
Site Characterizations	
Contaminants	Petroleum hydrocarbons in soil and groundwater, BTEX in groundwater only
Initial Contaminant Concentrations	
Phytotechnology Mechanisms	Phytoextraction
Vegetation Type	Hybrid poplar
Planting Descriptions	
Acreage	1 acre
Evapotranspiration Rates	
Climate	Temperature Range: -19 to 104F; Elevation: 804 ft; Mean annual precipitation: 36.6"; Growing season: 5/18-10/5
Operation/Maintenance Requirements	
Final Contaminant Concentrations	
Other Performance Data	Trees have degraded majority of BTEX compounds onsite, and are preventing contaminant migration. However, asymptotic levels of TPH ma have been reached in soil.
Cost	Annual operations and maintenance - $5,000
Funding Source	
Lessons Learned	
Comments	Site is being moved into new Ohio UST regulations promulgated in 2005 and anticipate closing site under a deed restriction and risk based actions.
Primary Contact	Wojciech Jozewicz, ARCADIS, WJozewicz@arcadis-us.com
Sources of Information	Email from Wojciech Jozewicz to Ellen Rubin, 29 June 2006.

Site Name	Abandoned Gasoline Station
Site Location	Axelved, Ronnede, Denmark
Project Scale	Field demonstration
Project Status	
Project Start Date	April 1999
Project Completion Date	
Media Treated	Soil
Site History and Background	The gas station operated from 1956 to 1990.
Site Characterizations	Contaminated soil is found up to 3 meters below ground surface.
Contaminants	Petroleum hydrocarbons from gasoline and diesel fuels
Initial Contaminant Concentrations	Petroleum hydrocarbons - More than 20,000 mg/kg
Phytotechnology Mechanisms	
Vegetation Type	Willows and poplars
Planting Descriptions	Stones were removed from the site, and the site was fertilized with 40 tons of chicken manure. Then 2,500 willow cuttings and 500 poplar cuttings were planted. Cuttings from surviving willows were used to fill in areas where plants had died in the first growing season in February 2000.
Acreage	1400 square meters
Evapotranspiration Rates	
Climate	
Operation/Maintenance Requirements	
Final Contaminant Concentrations	
Other Performance Data	Some cuttings died both inside and outside of the plume area in the first summer. In October 1999, willows growing in the area of highest contamination showed signs of phytotoxicity including yellowing of leaves, drying out, and even death. Trees grew well in less-contaminated areas. Cuttings of surviving willows were used to replace trees that had died. All trees survived in the second growing season. The majority of the willow hybrids were 2 - 3 meters tall in August 2000. A correlation between tree growth and concentration of hydrocarbons in soil was not seen, but that may be because the contaminants may be found at depths greater than 60 cm where the roots do not yet reach. No difference in frequency of fungi, insects, or disease was seen in trees growing in areas of varied levels of soil contamination.
Cost	
Funding Source	

Site Name	Abandoned Gasoline Station
Site Location	Axelved, Ronnede, Denmark
Lessons Learned	Trees survived higher concentrations in the field than they had in the lab, but that may be due to the depth at which the contaminants are found. Still, hotspots of contamination should be treated with other methods, while low to medium levels of hydrocarbon contamination can be treated with willows.
Comments	
Primary Contact	Ulrich Karlson, Dept. of Environmental Chemistry and Microbiology, National Environmental Research Institute, Denmark, uka@dmu.dk
Sources of Information	Trapp, S., A. Koehler, L.C. Larsen, K.C. Zambrano, and U. Karlson (2001) "Phytotoxicity of Fresh and Weathered Diesel and Gasoline to Willow and Poplar Trees" *Journal of Soils and Sediments* . 1(2): 71 - 76.

Site Name	Active Retail Gas Station
Site Location	Kenton, OH
Project Scale	Full-scale
Project Status	Complete
Project Start Date	1997
Project Completion Date	
Media Treated	Groundwater
Site History and Background	The site was an active retail gas station in a residential area.
Site Characterizations	There were three 10,000-gallon underground storage tanks at the site, and a release to soil and groundwater was discovered in 1993. The upper 20 feet at the site is glacial drift consisting predominantly of silty, sandy clay. Groundwater is first encountered found from 2 to 6 feet below ground surface (ft bgs) prior to remediation. Groundwater hydraulic conductivity was determined in slug tests to be 2.7E-5 to 5.2E-4 centimeters per second.
Contaminants	BTEX
Initial Contaminant Concentrations	
Phytotechnology Mechanisms	Hydraulic Control, Phytoextraction, Phytovolatilization, Rhizodegradation
Vegetation Type	Hybrid poplars, Black Willows, Maples
Planting Descriptions	A total of 58 trees were planted in two rows with 2.5 feet between trees in a row and four feet between rows. Most of the trees planted were whips, but between every three to five whips planted, one two-year-old rooted tree was planted. Twelve feed pipes were also installed every 12.5 feet along the rows to allow for future fertilizing. Seven piezometers were also installed to allow for monitoring of groundwater levels.
Acreage	0.6 acres
Evapotranspiration Rates	
Climate	Temperature Range: -19 to 101F; Elevation: 833 ft; Mean annual precipitation: 38.1"; Growing season: 5/9-10/3
Operation/Maintenance Requirements	Maintenance and monitoring was performed monthly during the first growing season and every other month in later seasons. Maintenance included fertilizing, trimming of low limbs and limbs near overhead wires, and spraying for insects three times per year. Monitoring included tree inspections, measurement of tree heights and diameters, water level measurements, and quarterly groundwater sampling.
Final Contaminant Concentrations	

Site Name	Active Retail Gas Station
Site Location	Kenton, OH
Other Performance Data	There was 100% tree survival through the first four growing seasons. Trees grew from a height of 2 to 3 feet to 10 to 15 feet in the first growing season and approximately 1 inch in diameter per year. Trees were planted approximately three feet below ground surface, and tree roots were observed as deep as 10 feet below ground surface three years later and extended about nine feet horizontally. A groundwater drop of 4.5 to 5.5 feet was observed in the third and fourth growing seasons. Dissolved oxygen is 125% higher in the planted area when compared to upgradient groundwater indicating that the trees are establishing a more favorable, aerobic environment for rhizodegradation.
Cost	Design - $3,500 Installation - $12,000 Annual operations and maintenance - $8,500 Installation costs were estimated to be 60 to 80 percent lower than traditional remedial techniques, and operations and maintenance costs were estimated to be 50 to 75 percent lower.
Funding Source	
Lessons Learned	
Comments	Currently requesting no further action.
Primary Contact	Wojciech Jozewicz, ARCADIS, WJozewicz@arcadis-us.com
Sources of Information	Golla, W. M. and J.J. Reid (2001) "Phytoremediation for hydraulic control of shallow groundwater impacted by petroleum hydrocarbons." In *Contaminated Soils* . P.T. Ksotecki, E.J. Calabrese, J. Dragun (Eds.), Amherst Scientific, Amherst, MA. 6: 45-59. Email from Wojciech Jozewicz to Ellen Rubin, 29 June 2006.

Phytoremediation of Petroleum Hydrocarbons

Site Name	Adjacent Retail Gasoline Outlets
Site Location	Raleigh, NC
Project Scale	Full scale
Project Status	Ongoing
Project Start Date	2003
Project Completion Date	
Media Treated	Groundwater
Site History and Background	
Site Characterizations	Groundwater is approximately 20 ft bgs.
Contaminants	Petroleum hydrocarbons
Initial Contaminant Concentrations	
Phytotechnology Mechanisms	Hydraulic control
Vegetation Type	Poplar and willow trees
Planting Descriptions	Trees were planted in rows roughly perpendicular to groundwater flow. Special cultural practices were used to encourage trees with very deep roots Deep boreholes were drilled at each planting location, the boreholes were backfilled with a sand/compost mixture, and the trees were planted in the backfill.
Acreage	
Evapotranspiration Rates	Rates of water use are 65 to 100 liters per day.
Climate	Temperature Range: -9 to 105F; Elevation: 443 ft; Mean annual precipitation: 41.4"; Growing season: 4/29-10/16
Operation/Maintenance Requirements	The young trees were irrigated using vertically installed subsurface drip lines, since the roots tend to follow the zone of moisture downward. Irrigation will be discontinued when the trees are sufficiently mature.
Final Contaminant Concentrations	
Other Performance Data	In the third growing season, roots had extended deeply in the backfill to within a few feet of the saturated zone. Rates of water use in the more contaminated area are lower suggesting that the groundwater contaminants may be somewhat inhibitory.
Cost	
Funding Source	
Lessons Learned	
Comments	The objective of the project is to hydraulically control the rate of plume migration. In 2006, the ratio of stable isotopes will be analyzed in xylem sap, groundwater, and vadose zone water to further assess the extent of groundwater uptake.
Primary Contact	Ari M. Ferro, Ph.D., Principal Technical Specialist, Phytoremediation, ENSR, (919) 872-6600, aferro@ensr.aecom.com
Sources of Information	Email from Ari Ferro, 30 June 2006.

Site Name	Amsterdam Terminal
Site Location	Netherlands
Project Scale	Full scale
Project Status	Ongoing
Project Start Date	2000
Project Completion Date	
Media Treated	Groundwater
Site History and Background	The site is an active facility, but a former petroleum refinery.
Site Characterizations	
Contaminants	Naphthalene
Initial Contaminant Concentrations	
Phytotechnology Mechanisms	Rhizodegradation, Hydraulic Control
Vegetation Type	Poplars, Willows
Planting Descriptions	
Acreage	2 to 3 acres
Evapotranspiration Rates	
Climate	
Operation/Maintenance Requirements	Plant health assessments, fertilizing, irrigation
Final Contaminant Concentrations	
Other Performance Data	
Cost	
Funding Source	BP
Lessons Learned	
Comments	
Primary Contact	David Tsao, BP Group Environmental Management Company, (630) 836-7169, tsaodl@bp.com
Sources of Information	Email from David Tsao, 17 July 2006.

Site Name	Argonne National Laboratory - 317/319 Area
Site Location	Lemont, Illinois
Project Scale	Full
Project Status	Ongoing
Project Start Date	1999
Project Completion Date	
Media Treated	Soil, Groundwater
Site History and Background	The 317/319 Area at Argonne National Laboratory contains several sites used in the past to dispose of solid and liquid waste from various laboratory activities.
Site Characterizations	Volatile organic compounds (VOCs) and tritium have been released in the groundwater at depths of approximately 6-9 meters (m) and have been detected in groundwater offsite. Geology at the site consists of 10 ft silty clay at the top, followed by 2 ft shallow aquifer, 8 ft silty clay, 10 ft silt and finally silty clay deep aquifer at the bottom. Groundwater encountered at 25 to 30 ft bgs.
Contaminants	Soil: Benzene, Carbon tetrachloride, Chloroform, Methylene chloride, Tetrachloroethene (PCE), Trichloroethene (TCE), 4-methyl-2-pentanone Groundwater: Carbon tetrachloride, Chloroform, Methylene chloride, TCE, 1,2-dichlorethane, cis-1,2-dichlorethene, Vinyl chloride, Tritium
Initial Contaminant Concentrations in Soil	Benzene - Up to 3.2 mg/kg Carbon tetrachloride - Up to 54 mg/kg Chloroform - Up to 21 mg/kg PCE - Up to 190 mg/kg TCE - Up to 47 mg/kg 4-methyl-2-pentanone - Up to 78 mg/kg
Initial Contaminant Concentrations in Groundwater	Carbon tetrachloride - Up to 8 micrograms per liter (ug/L) Chloroform - Up to 380 ug/L Methylene chloride - Up to 14 ug/L, PCE - Up to 50,000 ug/L TCE - Up to 8,600 ug/L 1,2-dichlorethane - Up to 6 ug/L cis-1,2-dichlorethene - Up to 240 ug/L Vinyl chloride - Up to 5 ug/L Tritium - Up to 233,000 picoCuries per liter (pCi/L)
Phytotechnology Mechanisms	Hydraulic Control, Phytodegradation, Phytostabilization
Vegetation Type	Hybrid Poplar, Eastern Gamagrass, Golden Weeping Willow, Hybrid Prairie Cascade Willow, Laurel-Leaved Willow

Site Name	Argonne National Laboratory - 317/319 Area
Site Location	Lemont, Illinois
Planting Descriptions	800 whips planted. 420 poplars installed in deep, lined boreholes (TreeWells). 389 willows and poplars planted at or near surface. The 317 Area French Drain area was also seeded with a mix of legumes and grasses to minimize water infiltration and to stabilize the soil. Used patented TreeWells and TreeMediation (Applied Natural Sciences Inc.) In 1999 Argonne installed a series of engineered plantings consisting of a vegetative cover system and approximately 800 hybrid poplars and willows rooting at various predetermined depths. Because of the peculiar stratigraphy at this site and the depth of the target contamination, the plants were installed using various methods including Applied Natural Sciences TreeWell® system which is designed to reach groundwater 30 feet below ground surface.
Acreage	4 acres
Evapotranspiration Rates	
Climate	Average maximum daily temperatures are highest during July (29C, 84F) and lowest during January (-2C, 29F). The Illinois State Climatologist's Office estimates that the median growing season for the area surrounding ANL-E is between 155 and 165 days. Summer thundershowers are often locally heavy and variable; parts of the Chicago area may receive substantial rainfall and other parts none. Longer periods of continuous precipitation are mostly in autumn, winter, and spring. Annual precipitation averages approximately 36", of which about 19" falls during the growing season (May through September). The amount of sunshine is moderate in summer and quite low in winter. A considerable amount of cloudiness, especially in winter, is locally produced by lake effect. Days in summer wit no sunshine are rare. The total sunshine in December, partly because of shorter days, is only a little over one-third the July total (GRC, 1977).
Operation/Maintenance Requirements	Fertilization, replanting, and significant Health/Safety expenditures because of radiological and other concerns
Final Contaminant Concentrations	

Site Name	Argonne National Laboratory - 317/319 Area
Site Location	Lemont, Illinois
Other Performance Data	Qualitatively results are good. Hydraulic control is apparent and VOCs have been detected in the plant tissue indicating uptake. But no quantitative results are available. From these data it is apparent that the trees have begun to influence the area. Only months after planting, both TCE and PCE were detected in branch tissue of trees growing in the source area soil. Correspondingly, trichloroacetic acid, a degradation intermediate, was consistently detected in leaves of these same plants. Two years after planting, TCE and PCE began to be detected also in tissue of several trees targeting the downgradient contaminant plume, and the number of detections has continued to increase with time. By the fall of 2002, several trees showed significantly higher tritium concentrations that approached the concentration of the groundwater in the area. Soil sample evidence shows that roots had developed at to at least 4 m by the fall of 2001.
Cost	The total project cost, which included designing, installing and maintaining the system for the first four years (1999-2002), was $2,382,632. The total estimated treatment cost over 20 years of the project is $4,592,632.
Funding Source	DOE
Lessons Learned	TreeWells installed in effort to achieve hydraulic control. During a warm period in September 2000, the plantation began exhibiting diurnal fluctuations (up to 7 centimeters) in groundwater elevation at selected monitoring wells. The diurnal fluctuations continued during the 2001 growing season and varied in amplitude with the amount of daily solar radiation. In 2001 water levels of some wells gradually lowered during days of high sunlight resulting in strong diurnal fluctuations. On cloudy days water level changes were less pronounced. These water level changes were an early indicator that the maturing trees will exert an increasing effect on the site's hydrology, which will ultimately result in hydraulic containment o the contaminant.
Comments	This progression was expected as a consequence of the time necessary for the roots to develop to the capillary fringe. Results of this modeling suggest that despite leaf-off winter periods, the plantation will provide full containment on the larger western (317 Area) side of the plantation, and a strong degree of containment on the eastern (319 Area) side.
Primary Contact	Cristina Negri, Argonne National Laboratory, Lemont, IL United States, Telephone: (603) 252-9662, E-mail: negri@anl.gov; Ed Gatliff , Applied Natural Sciences, United States, Telephone: (513) 895-6061, E-mail: ans@fuse.net

Site Name	Argonne National Laboratory - 317/319 Area
Site Location	Lemont, Illinois
Sources of Information	Phytoremediation at 317/319 Area, Argonne National Laboratory in Illinois, http://www.cluin.org/products/phyto/search/phyto_details.cfm?ProjectID=8 Deployment of Phytotechnology in the 317/319 Area at Argonne National Laboratory-East, Argonne, Illinois (2006), http://costperformance.org/profile.cfm?ID=390&CaseID=390 U.S. EPA (2003) *Deployment of Phytotechnology in the 317/319 Area at Argonne National Laboratory-East Innovative Technology Evaluation Report* . EPA 540-R-05-011, http://www.epa.gov/ORD/NRMRL/pubs/540r05011/540r05011.pdf Email from Cristina Negri, 3 August 2006.

Phytoremediation of Petroleum Hydrocarbons

Site Name	Ashland Inc. Facility
Site Location	Milwaukee, WI
Project Scale	Full
Project Status	Ongoing
Project Start Date	May 2000
Project Completion Date	
Media Treated	Soil, Groundwater
Site History and Background	Former chemical distribution facility and petroleum storage and distribution facility.
Site Characterizations	Groundwater contamination is highest in the eastern portion of the site near a former tank farm and drumming building. There are three underlying aquifers in the vicinity of the site, of which the two most shallow are unconfined at the site. Soil consists of fill, concrete and rock.
Contaminants	Petroleum hydrocarbons (gasoline- and diesel-range organics), BTEX, Chlorinated VOCs, and Semi-Volatile Organic Compounds
Initial Contaminant Concentrations in Soil	Ethylbenzene - 0.29 to 2,100 mg/kg Toluene - 0.18 - 590 mg/kg Xylenes - 1.0 - 780 mg/kg
Initial Contaminant Concentrations in Groundwater	Total Petroleum VOCs - 31.7 - 88.3 ug/L Total Chlorinated VOCs - 4.6 - 36.4 ug/L
Phytotechnology Mechanisms	Hydraulic Control, Phytoextraction, Phytovolatilization
Vegetation Type	Hybrid Poplar, Understory Grasses
Planting Descriptions	485 two-year-old hybrid poplar trees were planted in two areas at the site. Planting was performed using drill rigs to reach the desired planting depth. Originally, an air injection (aeration) system and a contingency irrigation system were also installed at the site. The aeration system was taken offline in 2003.
Acreage	0.4 acre
Evapotranspiration Rate	Estimated to be 34.2 inches/year for poplar trees.
Climate	Temperature range: -26 to 103 F; Elevation: 672 feet; Mean annual precipitation: 34"; Growing season: 4/1 to 10/1
Operation/Maintenance Requirements	Biweekly tree inspections, monitoring of groundwater levels in four wells, mowing weeding, composting, insecticide
Final Contaminant Concentrations	Concentrations of CVOCs have reduced approximately 77% to 99% and total PVOC concentrations have reduced approximately 81% to 95%.
Other Performance Data	Overall tree survival rate since 2000 remains approximately 90 percent. The trees, which werebetween five and ten feet tall when planted, are now mostly between 20 and 45 feet tall and are in good health.
Cost	$80,000
Funding Source	

Site Name	Ashland Inc. Facility
Site Location	Milwaukee, WI
Lessons Learned	
Comments	
Primary Contact	Jim Vondracek , RMT, Ashland, Inc., Milwaukee, WI United States, Telephone: (614) 790-646, E-mail: jevondracek@ashland.com
Sources of Information	Phytoremediation at Ashland Inc. in Wisconsin, http://www.cluin.org/products/phyto/search/phyto_details.cfm?ProjectID=9 URS Corporation (2006) *Year 2005 Operation, Maintenance, and Monitoring Report for Phytoremediation and Natura Attenuation, Ashland Distribution, Milwaukee, Wisconsin* . March 16, 2006. Email from Jim Vondracek, 14 August 2006.

Site Name	Atlas Tack Corp. Superfund Site
Site Location	Fairhaven, MA
Project Scale	Full-scale
Project Status	Ongoing; phytoremediation planned for Fall 2007.
Project Start Date	
Project Completion Date	
Media Treated	Groundwater
Site History and Background	The facility manufactured cut and wire tacks, steel nails, and similar items from 1901 to 1985.
Site Characterizations	
Contaminants	Toluene, ethyl benzene chromium, cadmium, lead, zinc and nickel, pesticides, PCBs, and PAHs
Initial Contaminant Concentrations	
Phytotechnology Mechanisms	Hydraulic control
Vegetation Type	
Planting Descriptions	
Acreage	
Evapotranspiration Rates	
Climate	Temperature range: -7 to 102F; Elevation: 30 feet; Mean annual precipitation: 41.5"; Growing season: 5/3-10/5
Operation/Maintenance Requirements	
Final Contaminant Concentrations	
Other Performance Data	
Cost	The 2000 Record of Decision estimated (without contingencies): * Cost of planting trees - $9,750 * Costs to monitor (sample) - $3,600 per year for 30 years * Cost to replant trees in year 2 (assumed 1/3 of trees need replacing) - $3,250
Funding Source	PRP
Lessons Learned	
Comments	Buildings were demolished in 2005, and cleanup of the upland soil and debris areas will commence in July 2006. Marsh soil and creek bed sediment will be remediated subsequent to the upland work. It is expected to take approximately 14 months to complete site cleanup depending on the availability of funding. Monitored natural attenuation will be performed until MCLs are met.
Primary Contact	Elaine Stanley, USEPA, 617-918-1332, stanley.elainet@epa.gov

Sources of Information	Email from Elaine Stanley, 23 June 2006. Waste Site Cleanup & Reuse in New England: Atlas Tack Corp., Fairhaven, Massachusetts, http://yosemite.epa.gov/r1/npl_pad.nsf/f52fa5c31fa8f5c885256adc0050b631/7F21321A3A6F9C90852568FF005ADB0C?OpenDocument

Site Name	Blockhouse Valley Landfill
Site Location	Oak Ridge, TN
Project Scale	Full-scale
Project Status	Ongoing
Project Start Date	2005
Project Completion Date	
Media Treated	Soil, Groundwater
Site History and Background	The Blockhouse Valley Landfill was operated from 1973 to 1983. The landfill was utilized for disposal of demolition debris and sanitary waste from surrounding communities. As landfilling reached its design capacity, disposal was shifted to the newly established landfill. Operations ceased at the Landfill in 1983, and the landfill cells were capped with clay, with closure completed by 1985.
Site Characterizations	Site studies were conducted that concluded that cap repairs were necessary to ensure its long-term stability. Faced with the probability of significant remediation costs to cap the entire 30 acre landfill, negotiations were conducted with the State to use an innovative approach to remedy the landfill. This remedy consisted of natural system of constructed wetlands and tree cap (hybrid poplars), meeting both stabilization goals and improving aesthetics of the area for nearby landowners. A remedy was ultimately proposed and approved by the State which includes institutional controls, monitoring, tree-cap, surface-water controls, and constructed treatment wetlands.
Contaminants	Benzene, Metals
Initial Contaminant Concentrations	Benzene - 875 ug/L Manganese - 29,580 ug/L
Phytotechnology Mechanisms	Hydraulic control
Vegetation Type	Hybrid poplar
Planting Descriptions	8,000 tree cuttings were planted in 2005 as part of an alternative vegetative cover system to limit percolation into the underlying waste. Trees were installed utilizing a single row ripper that was capable of opening a two-inch void that was three feet in depth. After installation, fertilizer was applied.
Acreage	15 acres
Evapotranspiration Rates	
Climate	Humid; Temperature range: -24 to 102F; Elevation: 981 feet; Mean annual precipitation: 47.1"; Growing season: 4/9-10/23
Operation/Maintenance Requirements	Site mowing during the initial years for establishment, weed and pest control, foliar sampling, fertilization, and inspection of trees for damage from insects and disease
Final Contaminant Concentrations	
Other Performance Data	

Site Name	Blockhouse Valley Landfill
Site Location	Oak Ridge, TN
Cost	Design - $50,000 Installation - $200,000 Annual operations and maintenance - $20,000 One estimate indicates that the approval of this remedy resulted in a savings of $4.6 million for the municipality.
Funding Source	
Lessons Learned	Weed control and planting techniques are critical to maximize tree growth during years one and two.
Comments	
Primary Contact	Berry Ilgner, ARCADIS, bilgner@arcadis-us.com
Sources of Information	Email from Wojciech Jozewicz (ARCADIS) to Ellen Rubin, 29 June 2006. ARCADIS Blockhouse Valley Landfill Litigation Support and Cap Stabilization Fact sheet. Email from Paul Preston (ARCADIS), 27 July 2006.

Site Name	Bofors Nobel
Site Location	Muskegon, MI
Project Scale	Full scale
Project Status	Pilot/field demonstration completed 2002. Completion of full-scale design is expected by October 2006, and installation is expected in March 2007.
Project Start Date	
Project Completion Date	
Media Treated	Soil, Groundwater
Site History and Background	Chemicals including alcohol-based detergents, saccharin, pesticides, herbicides, and dye intermediates were produced at the site, starting around 1960. Unlined lagoons were used for wastewater and sludge disposal at the site until approximately 1976. Site currently operates as a specialty chemical production facility.
Site Characterizations	Soil is sandy and tends to dry out quickly. Groundwater is found 6 to 40 feet below ground surface.
Contaminants	3,3 - Dichlorobenzidine, Acetone, Aniline, Arsenic, Benzene, Heavy Metal Tetrachloroethene, Toluene, Xylenes, Zinc
Initial Contaminant Concentrations	
Phytotechnology Mechanisms	Phytoextraction, Phytodegradation
Vegetation Type	Upland and wetland shrubs, hybrid poplars, white willows, and upland trees planned for full-scale installation.
Planting Descriptions	It is planned that approximately 790 upland and 360 wetland shrubs will be planted at four-foot spacing, approximately 550 hybrid poplars and white willows on 20-foot centers, approximately 400 upland trees on 30-foot centers, and only prairie seed mix of grasses and forbs will be spread in one area. Shrubs and willow/poplar tree species will be obtained as bare-root stock or live-cuttings. The upland tree species will be planted from containerized or balled and burlapped stock. The latter stock will be plants that are approximately 3-years-old and 3 to 4 ft in height.
Acreage	50 acres
Evapotranspiration Rates	
Climate	Temperature range: -15 to 99F; Elevation: 644 feet; Mean annual precipitation: 32.6"; Growing Season: 5/24-9/24.
Operation/Maintenance Requirements	In the pilot study, any tree species that did not survive in the contained area were cut down, trees were maintained on an irrigation system and were fertilized yearly, and trees were sprayed as need with insecticide and with a repellant to control browsing. Maintenance personnel also conducted monthly tree health evaluations. After successful full-scale installation, maintenance activity will continue at a minimum frequency of once per year.

Site Name	Bofors Nobel
Site Location	Muskegon, MI
Final Contaminant Concentrations	
Other Performance Data	In pilot testing, 115 trees (including 9 species, and 3 different "treatments") were planted in both contaminated sludge and uncontaminated soil in 15 replicate plots. Treatment 1: deep boreholes were drilled in the sludge, and backfilled with a sand/compost mixture, trees where then planted in the backfilled material; Treatment 2: the trees were planted directly in the sludge; Treatment 3: the trees were planted in uncontaminated soil. The tree species that clearly showed the best performance, as judged by high rate of survival, as well as good vigor and growth rate are: hackberry, honey locust, and bur oak. Certain species that were under-represented in the study also showed strong performance, including Black Hills spruce and jack pine. Species with fair performance were: Norway maple, hybrid poplar, and white willow. Eastern red cedar did poorly the first 2 years, but seemed to improve by the third growing season. The poplar and willow are riparian species with little tolerance to drought and showed signs of stress in the uncontaminated soil treatment.
Cost	Total remedy cost is estimated to be from about $15 million to $30 million.
Funding Source	Potentially Responsible Parties
Lessons Learned	
Comments	Phytoremediation is not the main goal of the remedy. The main goal is containment using the underground barrier (slurry) wall, with phytotechnology as an enhancement.
Primary Contact	John Fagiolo, USEPA, 312-886-0800, fagiolo.john@epa.gov
Sources of Information	Phytoremediation at Bofors-Nobel Superfund Site in Michigan http://www.cluin.org/products/phyto/search/phyto_details.cfm?ProjectID=10 NPL Fact Sheet for Michigan: Bofors Nobel, Inc. http://www.epa.gov/R5Super/npl/michigan/MID006030373.htm Email from John Fagiolo, 12 July 2006.

Phytoremediation of Petroleum Hydrocarbons

Site Name	Bus Depot
Site Location	Tampere, Finland
Project Scale	Field demonstration
Project Status	Complete
Project Start Date	June 2000
Project Completion Date	September 2003
Media Treated	Soil
Site History and Background	
Site Characterizations	Contaminated soil was a result of bus maintenance activities.
Contaminants	Aged lubricating oil and diesel fuel, lead
Initial Contaminant Concentrations	TPH - More than 11,000 mg/kg
Phytotechnology Mechanisms	Rhizodegradation
Vegetation Type	Pines, poplars, grasses, white clover
Planting Descriptions	Plot 1: Grass mixture and white clover with compost Plot 2: Pines, poplars, grass mixture, and white clover with municipal biowaste compost Plot 3: Pines, poplars, grass mixture, and white clover with NPK fertilizer Plot 4: Pines, poplars, grass mixture, and white clover with no amendments
Acreage	28 square meters
Evapotranspiration Rates	
Climate	
Operation/Maintenance Requirements	
Final Contaminant Concentrations	Plots 1 - 3: TPH > 3,000 mg/kg Plot 4: TPH > 8,000 mg/kg
Other Performance Data	The unfertilized plot had the lowest density of vegetation and did not see a significant decline in hydrocarbons concentrations. 60 - 65% removal was seen in plots treated with amendments; however, no significant difference was seen between plots with and without trees. Soil toxicity was also evaluated. Soil toxicity to Vibrio fischeri (a marine bacterium) and E. albidus (earthworms) was low, and soil leachate was not toxic to V. fischeri.
Cost	
Funding Source	
Lessons Learned	Compost addition combined with a grass and legume crop is suggested for stabilization of combined hydrocarbon- and metal-contaminated soil.
Comments	
Primary Contact	Marja Palmroth, marja.palmroth@gmail.com

Site Name	Bus Depot
Site Location	Tampere, Finland
Sources of Information	Palmroth, M., P. Koskinen, J. Pichtel, K. Vaajasaari, A. Joutti, T. Tuhkanen, and J. Puhakka (2006) "Field-Scale Assessment of Phytotreatment of Soil Contaminated with Weathered Hydrocarbons and Heavy Metals" *Journal of Soils and Sediments.* 6 (3) 128-136. Palmroth, M. (2006) "Enhancement of In Situ Remediation of Hydrocarbon Contaminated Soil," PhD Dissertation, Tampere University of Technology, Institute of Environmental Engineering and Biotechnology.

Phytoremediation of Petroleum Hydrocarbons

Site Name	Carteret Terminal
Site Location	NJ
Project Scale	Full scale
Project Status	Complete
Project Start Date	2000
Project Completion Date	2006
Media Treated	Groundwater
Site History and Background	Active petroleum refinery
Site Characterizations	
Contaminants	BTEX, Methyl tert butyl ether (MTBE)
Initial Contaminant Concentrations	
Phytotechnology Mechanisms	Phytodegradation, Rhizodegradation, Hydraulic Control, Phytovolatilization
Vegetation Type	Poplars
Planting Descriptions	
Acreage	<1 acre
Evapotranspiration Rates	
Climate	Temperature range: -8 to 105F; Elevation: 7 feet; Mean annual precipitation: 43.9"; Growing Season: 4/15-10/26.
Operation/Maintenance Requirements	Plant health assessments, fertilizing, irrigation
Final Contaminant Concentrations	
Other Performance Data	
Cost	
Funding Source	BP
Lessons Learned	
Comments	
Primary Contact	David Tsao, BP Group Environmental Management Company, (630) 836-7169, tsaodl@bp.com
Sources of Information	Email from David Tsao, 17 July 2006.

Site Name	Charleston Manufactured Gas Plant site
Site Location	Charleston, SC
Project Scale	600 trees originally planted, down to 400 trees due to construction activities
Project Status	Ongoing
Project Start Date	November 1998
Project Completion Date	
Media Treated	Soil, groundwater
Site History and Background	Since 1850, a variety of manufacturing processes and industry's related to the coal gasification
Site Characterizations	Water table from 2-4 ft below ground surface. Groundwater is anoxic. BTEX and PAH are present in dissolved phase, and some pockets of Dense non aqueous phase liquid (DNAPL) are encountered at the bottom of the aquifer on top of clays.
Contaminants	BTEX, PAHs
Initial Contaminant Concentrations	Milligrams per liter in ground water
Phytotechnology Mechanisms	Phytoextraction, Phytodegradation, Phytovolatilization, Rhizodegradation
Vegetation Type	Hybrid poplar trees
Planting Descriptions	Surface contaminated soils removed to a depth of 3 ft in 1998; backfilled with clean topsoil; 6-ft whips installed. May 2000, 6-foot whips installed to increase coverage, inserted in 4-in diameter holes constructed with power auger.
Acreage	
Evapotranspiration Rates	
Climate	Semitropical, coastal, zone 8-9; Temperature range: 6 to 104F; Elevation: 49 feet; Mean annual precipitation: 41.5"; Growing season: 4/6-10/30
Operation/Maintenance Requirements	Move grass beneath trees every 2-weeks from April to November. Prune in December. Remove dead branches and trees, as needed. Trees and groundwater are monitored on a quarterly basis.
Final Contaminant Concentrations	Concentrations in groundwater have decreased since 1998; paper in preparation that details the results to date.
Other Performance Data	
Cost	Ongoing costs approximately $50,000 per year
Funding Source	Federal-state cooperative program
Lessons Learned	
Comments	No need to use herbicides if some cottonwood leaf beetles show up.
Primary Contact	James E. Landmeyer, PhD, USGS, jlandmey@usgs.gov
Sources of Information	Emails from James E. Landmeyer, 2 August 2006 and 15 August 2006.

Phytoremediation of Petroleum Hydrocarbons

Site Name	Combustion Inc. Superfund site
Site Location	Denham Springs, LA
Project Scale	Full-scale
Project Status	Ongoing
Project Start Date	2001
Project Completion Date	
Media Treated	Groundwater
Site History and Background	Site is a waste oil recycling facility from the late 1960s until the early 1980s.
Site Characterizations	There are two water-bearing zones at the site. The top of the upper water-bearing zone is generally encountered at depths ranging from 4 to 18 ft bgs and the base is variable but no greater than 30 ft bgs. Top of the lower water-bearing zone ranges from 26 to 42 ft bgs, and the base ranges from 59 to 102 ft bgs. Impacted groundwater is found within the upper water-bearing zone no greater than 30 ft deep.
Contaminants	2,4/2,6-Toluenediamine, o-Toluidine, p-Toluidine, 1,1,2-Trichloroethane, 1,1-dichloroethane, 1,1-dichloroethene, 1,2-dichloroethane, acetone, benzene, chloromethane, cis-1,2-dichlorotethene, methylene chloride, tetrachloroethene, toluene, vinyl chloride
Initial Contaminant Concentrations	
Phytotechnology Mechanisms	Hydraulic Control, Phytodegradation
Vegetation Type	Eucalyptus, Poplars, Native Pines, Willows, Oaks, Cottonwood, and Sycamore
Planting Descriptions	Five stands of trees initially planted in 2001. Trees added and replaced in 2005. Two additional stands planted 2006. For the initial five stands, poplars were rootless cuttings (432 trees) and eucalyptus were planted rootball stock (550 trees). They were planted in 12 inch diameter, 6 feet depth holes and backfilled with sand/mulch/soil. The initial five stands required the removal/replacement/addition of 370 trees. In the final two stands, a variety of species (398 trees) 0.75 inches to 1.5 inches in diameter from commercial nursery stock were planted on a 10-foot grid.
Acreage	3.7 acres
Evapotranspiration Rates	Unknown at this time, but will be estimated in the future.
Climate	Temperature range: -8 to 102 F with average winter temperature of 51 F and average summer temperature of 81 F; Elevation: 50 to 53 feet above mean sea level: Mean annual precipitation: 58.05 inches; Growing season: 3/18 to 11/14.
Operation/Maintenance Requirements	Tree maintenance and growth surveys, groundwater monitoring

Site Name	Combustion Inc. Superfund site
Site Location	Denham Springs, LA
Final Contaminant Concentrations	
Other Performance Data	
Cost	Actual cost reported by the PRP: Tree planting: $229,040 (~1,500 trees in designed-backfill boreholes with breather tubes and sub-irrigation system) Tree establishment: $41,450 Miscellaneous items: $54,000; Total Direct Costs: $324,580 Engineering services: 25% of Direct Costs Construction services: 20% of Direct Costs Permitting and Legal services: 10% of Direct Costs Contingency: 30% of Direct Costs Total Capital: $654,000 Annual sampling: $8,421 Analytical: $11,869 Reporting: $8,517 Purge water disposal: $1.00 Phytotechnology maintenance: $35,000 (this number has increased as a result of several trees toppling over in hurricanes over the years) Miscellaneous items: $13,000 Total Operation and Maintenance: $78,400 per year Phytoremediation Total: $1,859,000
Funding Source	Potentially Responsible Party
Lessons Learned	Initial use of the drip irrigation system did not allow the root systems to develop at depth resulting in many trees with shallow circular root systems. This lack of maintenance and trees care required the expertise of an arborist.
Comments	The remedial alternative for this site is Phytoremediation with Monitored Natural Attenuation. During the five-year review, the groundwater data will be evaluated to ensure that the goal of a 10% mean concentration reduction is reached. If it is determined that this is not the case, then the contingency remedy, Hot Spot Treatment will be used.

Site Name	Combustion Inc. Superfund site
Site Location	Denham Springs, LA
Primary Contact	Katrina Higgins-Coltrain, USEPA, (214) 665-8143 Todd Thibodeaux, LDEQ, (225) 219-3225 David Tsao, BP Group Environmental Management Company, (630) 836-7169, tsaodl@bp.com
Sources of Information	Phytoremediation at the Combustion Inc. Superfund site in Louisiana http://www.cluin.org/products/phyto/search/phyto_details.cfm?ProjectID=12 NPL Fact Sheet - Combustion, Inc., Livingston Parish, Louisiana, June 2006 http://www.epa.gov/earth1r6/6sf/pdffiles/0600472.pdf Email from Katrina Higgins-Coltrain, 20 July 2006.

Site Name	Craney Island Fuel Terminal
Site Location	Portsmouth, VA
Current/Former Uses of the Site	Gasoline Service Station/Petroleum Storage Facility
Project Scale	Pilot/Field Demonstration
Project Status	Complete
Project Start Date	1995
Project Completion Date	1997
Media Treated	Soil
Site Characterizations	The soil is 21 percent silt, 19 percent clay, and 2.5 milliequivalents per liter sand.
Contaminants	TPH, Diesel fuel, Lead
Initial Contaminant Concentrations	
Phytotechnology Mechanisms	Rhizodegradation, Phytodegradation
Vegetation Type	Bermuda grass, Rye grass, White clover, Tall fescue
Planting Descriptions	Phytoremediation is in a biological treatment cell containing a 12-18 inch layer of contaminated soil, followed by a sand layer, a polyethylene liner, another sand layer, a geogrid layer, and finally a compacted clay base. Vegetation was planted at the site via seeding.
Acreage	2.01 acres
Evapotranspiration Rates	
Climate	Temperature range: -3 to 104F; Elevation: 26 feet; Mean annual precipitation: 44.6"; Growing season: 4/6-10/31.
Operation/Maintenance Requirements	Monthly basis: weeding, mowing, fertilization (44 pounds Nitrogen/acre, 1 pounds Phosphorous/Acre). TPH and nutrient sampling monthly or bimonthly. Tilling and irrigation when necessary. Reseeding of fescue and clover in 1996.
Final Contaminant Concentrations	
Other Performance Data	Total TPH degradation in soils varied by vegetative treatment. November 1996 data: Bermuda grass: 31% TPH reduction in soils; tall fescue: 35% reduction; white clover: 37% reduction, and unvegetated areas: 25% reduction.
Cost	
Funding Source	Advanced Applied Technology Demonstration Facility (AATDF) and the U.S. Department of Defense (DoD)
Lessons Learned	
Comments	

Site Name	Craney Island Fuel Terminal
Site Location	Portsmouth, VA
Primary Contact	M. K. Banks Purdue University IL United States Telephone: (765) 496-3424 E-mail: kbanks@ecn.purdue.edu
Sources of Information	Phytoremediation at the Craney Island Fuel Terminal in Virginia http://www.cluin.org/products/phyto/search/phyto_details.cfm?ProjectID=121 Hutchinson, S.L., A.P. Schwab, and M.K. Banks (2003) "Biodegradation of Petroleum Hydrocarbons in the Rhizosphere," In: *Phytoremediation: Transformation and Control of Contaminants* . S.C. McCutcheon and J.L. Schnoor (eds.), John Wiley & Sons, Inc. Hoboken, New Jersey. 355-386.

Site Name	Crude Oil-Contaminated Freshwater Wetland on the St. Lawrence River
Site Location	Ste. Croix de Lotibiniere, Canada
Project Scale	Field demonstration
Project Status	Complete
Project Start Date	June 1999
Project Completion Date	
Media Treated	Sediment
Site History and Background	
Site Characterizations	Soil at the site is a sandy loam (58% sand, 32% silt, and 10% clay).
Contaminants	Artificially weathered Mesa light crude oil
Initial Contaminant Concentrations	
Phytotechnology Mechanisms	Rhizodegradation
Vegetation Type	Predominant plant species is Three-Square Bulrush.
Planting Descriptions	Work was performed on an existing freshwater wetland at the site. Treatments included: No oil and nutrients Oil but no nutrients Oil and various nutrients Oil and nutrients but with plants cut back to ground surface 12 L of oil was applied to those treatment plots receiving oil, corresponding to a penetration depth of 2 cm.
Acreage	
Evapotranspiration Rates	
Climate	
Operation/Maintenance Requirements	
Final Contaminant Concentrations	
Other Performance Data	Alkane degraders increased only marginally in all treatments, while PAH degraders increased by 3.5 orders of magnitude in response to exposure to crude oil. No significant treatment effects were observed due to fertilizer addition. About 35% biodegradation of total alkanes and PAHs occurred in all treatments on average through the first 147 days. Generally, at that point, there were no significant treatment differences among any of the treatments.
Cost	
Funding Source	
Lessons Learned	The primary mechanism of oil mass loss from all plots, regardless of treatment, was physical rather than biological. The most important limitation for cleanup of an oil-contaminated wetland is oxygen availability.

Site Name	Crude Oil-Contaminated Freshwater Wetland on the St. Lawrence River
Site Location	Ste. Croix de Lotibiniere, Canada
Comments	
Primary Contact	
Sources of Information	Venosa, A.D. , K. Lee, M.T. Suidan, S. Garcia-Blanco, S. Cobanli, M. Moteleb, J.R. Haines, G. Tremblay, and M. Hazelwood (2002) "Bioremediation and Biorestoration of a Crude-Oil Contaminated Freshwater Wetland on the St. Lawrence River,"*Bioremediation Journal* . 6(3): 261-281.

Site Name	Crude Oil Spill Site
Site Location	Southeast Texas
Project Scale	Field demonstration
Project Status	Complete
Project Start Date	February 1994
Project Completion Date	May 1996
Media Treated	Soil
Site History and Background	Site was an agricultural field.
Site Characterizations	Soil is 35% sand, 30% silt, and 35% clay.
Contaminants	TPH
Initial Contaminant Concentrations	
Phytotechnology Mechanisms	Rhizodegradation
Vegetation Type	Sorghum, Rye grass, St. Augustine grass
Planting Descriptions	A phytoremediation treatment grid was established comprising four rectangular plots, each 18 x 9 m in size and seeded with each of the three plant types and one that was not seeded and acted as a control. The control plot was treated with an herbicide and had no vegetation on it.
Acreage	4 plots of 9m x 18m
Evapotranspiration Rates	
Climate	Long, hot summers and very mild winters; Temperature range: 7 to 107F; Elevation: 102 feet; Mean annual precipitation: 47"; Growing season: 3/17-11/14.
Operation/Maintenance Requirements	Fertilizer was applied approximately every two months at a rate of 116 pounds of nitrogen per acre and 58 pounds of phosphorus per acre.
Final Contaminant Concentrations	
Other Performance Data	TPH concentration in the rye grass plot reduced to 42% of its initial value after 21 months. TPH concentrations in the rye grass plot was reduced 50% in 21 months. Reduction of the mean concentrations for the St. Augustine grass and rye grass was about 25% greater than in the sorghum or unvegetated control plots.
Cost	
Funding Source	
Lessons Learned	
Comments	
Primary Contact	M. K. Banks, Purdue University, (765) 496-3424, kbanks@ecn.purdue.edu

Site Name	Crude Oil Spill Site
Site Location	Southeast Texas
Sources of Information	Nedunuri, K.V.; R.S. Govindaraju; M.K. Banks; A.P. Schwab; and Z. Chen (2000) "Evaluation of Phytoremediation for Field-Scale Degradation of Total Petroleum Hydrocarbons" *Journal of Environmental Engineering* . 126 (6): 483 - 490. Hutchinson, S.L., A.P. Schwab, and M.K. Banks (2003) "Biodegradation of Petroleum Hydrocarbons in the Rhizosphere," In: *Phytoremediation: Transformation and Control of Contaminants* . S.C. McCutcheon and J.L. Schnoor, eds, John Wiley & Sons, Inc. Hoboken, New Jersey. Pp. 355-386.

Phytoremediation of Petroleum Hydrocarbons

Site Name	Doraville Terminal
Site Location	GA
Project Scale	Full scale
Project Status	Ongoing
Project Start Date	1999
Project Completion Date	
Media Treated	Groundwater, Surface water seeps
Site History and Background	Active petroleum refinery
Site Characterizations	
Contaminants	Petroleum hydrocarbons (diesel range)
Initial Contaminant Concentrations	
Phytotechnology Mechanisms	Rhizodegradation, Hydraulic Control
Vegetation Type	Various prairie species (including clump grasses and wildflowers)
Planting Descriptions	
Acreage	<1 acre
Evapotranspiration Rates	
Climate	Long, hot summers and very mild winters; Temperature range: -8 to 105F; Elevation: 977 feet; Mean annual precipitation: 50.8"; Growing season: 4/10-10/25.
Operation/Maintenance Requirements	Plant health assessments, fertilizing, irrigation
Final Contaminant Concentrations	
Other Performance Data	
Cost	
Funding Source	BP
Lessons Learned	
Comments	
Primary Contact	David Tsao, BP Group Environmental Management Company, (630) 836-7169, tsaodl@bp.com
Sources of Information	Email from David Tsao, 17 July 2006.

Site Name	Edward Sears Property
Site Location	New Gretna, New Jersey
Project Scale	Pilot/Field Demonstration
Project Status	Ongoing
Project Start Date	December 1996
Project Completion Date	2004
Media Treated	
Site History and Background	From the mid 1960s to the early 1990s, the property was used for repackaging and sale of paints, adhesives, paint thinners, and various military surplus materials. As a result, toxic materials were stored in leaky drums and containers on his property for many years. The soil and groundwater were contaminated with numerous hazardous wastes, includin dichloromethane, PCE, TCE, TMB, and xylenes. A demonstration of phytoremediation to clean up shallow groundwater was performed at the sit was performed by the U.S. Air Force as part of the Department of Defense' Environmental Security Technology Certification Program and the SITE Program. In 1994 to 1995, the EPA Region II Removal Program removed and disposed of approximately 4,000 containers ranging in size from pints to 55-gallon drums. In addition, 450 cubic yards of contaminated soil was removed to a depth of 5 feet, where a tight clay was encountered and reduced further penetration of contaminants.
Site Characterizations	Groundwater is 7 to 11 ft bgs. Groundwater is also subject to tidal influence of about 1-foot per cycle. There is a highly permeable sand layer from 0 to 5 ft bgs, underlain by a much less permeable layer of sand, silt, and clay from 5 to 18 ft bgs. This silt, sand, and clay layer acts as a semi-confining unit for water and contaminants percolating down toward an unconfined aquifer from 18 to 80 ft bgs. This unconfined aquifer is composed primarily of sand and is highly permeable. The top of the aquifer is about 9 ft bgs, which lies in the less permeable sand, silt, and clay layer. The top of the aquifer is relatively shallow and most of the contamination is confined from 5 to 18 ft bgs.
Contaminants	Methylene chloride, PCE, TCE, Dichloromethane, 1,3,5-Trimethylbenzene (TMB), Xylenes
Initial Contaminant Concentrations in Soil	PCE - 0.100 to 0.160 mg/kg TCE - 0.035 to 0.390 mg/kg Dichloromethane - 0.0012 to 0.615 mg/kg
Initial Contaminant Concentrations in Groundwater	Methylene chloride - 6,700 ug/L PCE - 160 ug/L TCE - 390 to 510 ug/L Dichloromethane - 490,000 ug/L 1,3,5-Trimethylbenzene - 2,000 ug/L Xylenes - 2,700 ug/L

Site Name	Edward Sears Property
Site Location	New Gretna, New Jersey
Phytotechnology Mechanisms	Hydraulic Control, Phytodegradation
Vegetation Type	Hybrid Poplar
Planting Descriptions	In December 1996, 118 hybrid poplar trees were planted 9 ft bgs in a plot approximately one-third of an acre in size; in addition, some trees were planted along the boundary of the site at 3 ft bgs (shallow rooted) to minimize groundwater and rainwater infiltration from off-site. The trees were planted 10 ft apart on the north to south axis and 12.5 ft apart on the east-west axis. Holes were drilled and plants installed, and backfilled with sand peat mix. 100 trees planted shallow 3 foot below ground surface. Holes drilled to top of clay 4 to 5 feet below grade. The trees were planted using a process called deep rooting: 12 foot trees were buried 9 feet under the ground so that only 2-3 feet of tree remained on the surface. This was done to enhance deep rooting of poplar trees in the zone of contamination, and to maximize uptake of groundwater compared to surface water.
Acreage	1 acre
Evapotranspiration Rates	
Climate	Temperature range: -2 to 102 F; Elevation: 52 feet; Mean annual precipitation: 26.7"; Growing season 5/19-9/28
Operation/Maintenance Requirements	NPK and lime added annually. Site maintenance involves fertilization, and control of insects, deer, unwanted vegetation, drought, and vandalism. Monitoring has included extensive groundwater sampling data as well as sap flow and annual growth measurements.
Final Contaminant Concentrations	Dichloromethane was reduced over the first 3 years of monitoring, with concentrations at 4 locations decreasing from 490,000 down to 615 ppb, 12,000 parts per billion (ppb) to below detection limits (ND), 680 ppb to ND, and 420 to 1.2 ppb. PCE was reduced at 1 location from 100 to 56 ppb. TCE increased at 1 location from 9 to 35 ppb, but decreased at another location from 99 to 42 ppb; at other locations TCE remained stable over the 3 year period. TMB was reduced from 147 to 2 ppb, 246 to ND, 1900 to 50 ppb, and 8 to 1 ppb at four microwell points in the treated area; at another well point within the treated area, concentrations of TMB were relatively unaffected, 102 ppb in August 1997 compared to 128 in August 1999. Xylenes were unaffected or slightly increased at 1 location, 26 ppb in August 1997 compared to 34 ppb in August 1999; at two other locations, xylene concentrations dropped from 590 to 17 ppb, and from 56 to 1.4 ppb.
Other Performance Data	Some of the trees are now more than 50-feet tall.

Site Name	Edward Sears Property
Site Location	New Gretna, New Jersey
Cost	The total cost for installation was $105,000, consisting of $24,000 for site preparation, $65,700 for planting; and $15,300 for maintenance. Monitoring/analysis: 50 groundwater stations, soil gas, soils, hydrogeological parameters, weather, transpiration gas, reports, etc. Monitoring costs should also reduce annually as study techniques become more refined: 1997 - $72,800; 1998 - $61,600; 1999 - $42,000.
Funding Source	U.S. Air Force
Lessons Learned	There seems to have been an adverse impact on tree growth in areas with high VOCs concentrations during the initial two growing seasons. However in the third growing season, the rate of growth has increased significantly but the trees have yet to achieve the height and diameter of trees planted in uncontaminated areas.
Comments	Contamination in sand/silt/clay unit, most plants survived, dichloromethane concentrations substantially reduced in groundwater, and TCE has also been reduced after six years of treatment.
Primary Contact	George R. Prince, USEPA, (732) 321-6649, prince.george@epamail.epa.gov Christopher Gussman, Lockheed Martin/REAC, (732) 321-4237, christopher.d.gussman@lmco.com
Sources of Information	Phytoremediation at the Edward Sears Property in New Jersey http://www.cluin.org/products/phyto/search/phyto_details.cfm?ProjectID=13

Site Name	Experimental Dredged Sediment Disposal Sites
Site Location	Menen, Belgium
Project Scale	Field demonstration
Project Status	Complete
Project Start Date	July 1999
Project Completion Date	Beginning of 2004
Media Treated	Dredged sediment
Site History and Background	Two sites for disposal of dredged sediment were established and filled with one meter of sediment from the River Leie for purposes of this project.
Site Characterizations	
Contaminants	Mineral oil, PAHs, Zinc, Cadmium
Initial Contaminant Concentrations	Mineral oil - 245.2 to 364 mg/kg Total PAHs - 8.29 to 11.88 mg/kg
Phytotechnology Mechanisms	
Vegetation Type	Willows
Planting Descriptions	Willow trees were planted in the wet sediment in one of the disposal sites, and all vegetation was continually removed from the other. Willows were planted using the SALIMAT technique in which 2-meter long willow rods are tied together with a biodegradable string and then rolled around a centra disposable tube. The tubes are then dragged across the area to be planted, and after the tube sinks into the sediment, the willow rods will sprout quickly thereafter, and a stand is established.
Acreage	Two 20m x 20m plots
Evapotranspiration Rates	
Climate	
Operation/Maintenance Requirements	
Final Contaminant Concentrations	
Other Performance Data	A high density willow stand had developed one week after planting. Shoot density declined in the second growing season due to competition in the stand. In two growing seasons, mineral oil concentration declined 57% in the vegetated plot compared to 15% in the control plot. In contrast, the control plot saw a decline in total PAH concentration of 32% compared to only 13% in the vegetated plot. The disappearance of both mineral oil and PAHs declined as the depth below ground surface increased.
Cost	
Funding Source	

Site Name	Experimental Dredged Sediment Disposal Sites
Site Location	Menen, Belgium
Lessons Learned	Since mineral oil and PAHs reacted differently to the planting of a high-density willow stand, perhaps different microbial processes are responsible for their degradation. The control plot may have benefited from greater aeration and direct sunlight and rainfall.
Comments	
Primary Contact	Jan Mertens, Ghent University, Jan.Mertens@UGent.be
Sources of Information	Vervaeke, P., S. Luyssaert, J. Mertens, E. Meers, F.M.G. Tack, and N. Lust (2003) "Phytoremediation prospects of willow stands on contaminated sediments: a field trial" *Environmental Pollution* . 126: 275 - 282. Vervake, P., S. Luyssaert, J. Mertens, B. De Vos, L. Speleers, N. Lust (2001) "Dredged sediment as a substrate for biomass production of willow trees established using the SALIMAT technique" *Biomass and Bioenergy* . 21: 81 - 90.

Phytoremediation of Petroleum Hydrocarbons

Site Name	Former Chevron Terminal
Site Location	Ogden, UT
Project Scale	Full-scale
Project Status	Ongoing
Project Start Date	1996
Project Completion Date	
Media Treated	Groundwater
Site History and Background	Site was a gasoline service station and petroleum storage facility from 1950s until 1989.
Site Characterizations	Depth to groundwater is approximately 2 to 3 ft bgs in spring and 7 to 8 ft bgs in the fall. Soil is a silty sand. Hydraulic gradient is 0.019 ft/ft.
Contaminants	BTEX, Petroleum hydrocarbons
Initial Contaminant Concentrations	Petroleum hydrocarbons - 50 to 500 mg/L
Phytotechnology Mechanisms	Hydraulic control
Vegetation Type	Hybrid poplars
Planting Descriptions	Three dense rows of deep-rooted poplar trees were planted along the downgradient edge of a plume of TPH-contaminated groundwater (April 1995, 145 trees and April 1996, 40 trees). Trees were planted 7.5 ft apart with 6 feet between rows. Trees were planted in moist soil at the bottom of an eight foot deep borehole. Since the trees were dependent upon groundwater even during their first growing season, no surface irrigation was necessary. In addition, nine ft of PVC pipe were placed in each borehole to move oxygen to the subsurface.
Acreage	3,000 square ft
Evapotranspiration Rate	Historically, in the growing season, evapotranspiration rate varies from 2.86 inches in October to 9.77 inches in July while precipitation is between 0.57 inches in July and 2.05 inches in April.
Climate	Arid; Temperature range: -18 to 104 F; Elevation: 4,225 feet; Mean annual precipitation: 16.2"; Growing season 5/18-9/29.
Operation/Maintenance Requirements	The stand was never irrigated.
Final Contaminant Concentrations	
Other Performance Data	Water use by the stand in 1999 averaged 445 gallons per day, a volume equivalent to a 10-ft thickness of the saturated zone. However, a depression in water table elevation was not noted.
Cost	Cost including site preparation, planting, irrigation system, and maintenanc (but not analytical) - $ 50,000
Funding Source	
Lessons Learned	
Comments	

Site Name	Former Chevron Terminal
Site Location	Ogden, UT
Primary Contact	Ari M. Ferro, Ph.D., Principal Technical Specialist, Phytoremediation, ENSR, (919) 872-6600, aferro@ensr.aecom.com
Sources of Information	Ferro, A., J. Chard, R. Kjelgren, B. Chard, D. Turner, and T. Montague (2001). "Groundwater Capture Using Hybrid Poplar Trees: Evaluation of a System in Ogden Utah" *International Journal of Phytoremediation* . 3: 1 (87 - 104). Email from Ari Ferro, 30 June 2006. www.epareachit.org

Phytoremediation of Petroleum Hydrocarbons

Site Name	Former Industrial facility
Site Location	Stratford, WI
Project Scale	
Project Status	
Project Start Date	1994
Project Completion Date	
Media Treated	Soil
Site History and Background	
Site Characterizations	Contamination resulted from a release of fuel oil from underground piping and remains in four separate areas. The first 3 to 15 feet below ground surface are heterogeneous fill material. Concentrations in groundwater are below state water quality standards. Depth to groundwater is 3 to 9 ft.
Contaminants	DRO
Initial Contaminant Concentrations	DRO - More than 1,000 mg/kg
Phytotechnology Mechanisms	Rhizodegradation
Vegetation Type	Hybrid willows
Planting Descriptions	300 trees were planted at a spacing of 8 ft. TreeMediation planting process (developed by Applied Natural Sciences) was used to have root zone at the depth of contamination.
Acreage	1 acre
Evapotranspiration Rates	
Climate	Temperature range: -34 to 105 F; Elevation: 833 feet; Mean annual precipitation: 28.4"; Growing season 5/21-9/15.
Operation/Maintenance Requirements	Included tissue sampling, fertilizer and insecticide applications, watering, pruning, and observing the overall health and growth of the trees.
Final Contaminant Concentrations	
Other Performance Data	Trees have grown an average of 4 to 6 ft in height. Trunk diameters have gotten as large as 4 inches. Only 2% of planted trees died. In two of the contaminated areas, geometric mean of concentration of diesel range organics in soil declined 66 and 68%. One area showed no clear trend in concentrations, and the fourth could not be sampled sufficiently to analyze concentration trends.
Cost	
Funding Source	
Lessons Learned	
Comments	
Primary Contact	Wojciech Jozewicz, ARCADIS, WJozewicz@arcadis-us.com

Site Name	Former Industrial facility
Site Location	Stratford, WI
Sources of Information	Carman, E.P., T.L. Crossman, and K.L. Daleness (2000). "In-Situ Bioremediation of #2 Fuel Oil Utilizing Phytoremediation" In *Bioremediation and Phytoremediation of Chlorinated and Recalcitrant Compounds* . G. B. Wickramanayake, A.R. Gavaskar, B.C. Alleman, and V.S. Magar (eds.) Batelle Press, Columbus, OH: 501 - 508.

Site Name	Former Industrial Sludge Basin
Site Location	Southeast Texas
Project Scale	
Project Status	
Project Start Date	
Project Completion Date	
Media Treated	Soil
Site History and Background	Industrial sludge basin at an organic chemical manufacturing plant
Site Characterizations	Effluent from a primary clarifier containing a mixture of contaminants and sediments was discharged into the basin from the 1940s to the early 1980s.
Contaminants	PAHs
Initial Contaminant Concentrations	Not available.
Phytotechnology Mechanisms	
Vegetation Type	Dominant plant species include mulberry trees, Bermuda grass, and common sunflowers.
Planting Descriptions	After wastewater was no longer being discharged to the basin, water was drained of any existing surface water and thereafter naturally revegetated.
Acreage	1.1 acres
Evapotranspiration Rates	
Climate	Temperature range: 7 to 107F; Elevation: 102 feet; Mean annual precipitation: 47"; Growing season: 3/17-11/14.
Operation/Maintenance Requirements	
Final Contaminant Concentrations	
Other Performance Data	Since historic concentration data was not available, contaminant concentrations throughout the root zone were compared to contaminant concentrations in the "parent sludge" below the root zone. Total PAHs 0 to 30 cm below ground surface - Average of 1,121 mg/kg Total PAHs 30 to 60 cm below ground surface - Average of 2,645 mg/kg Total PAHs at the bottom of the root zone - Average of 9,191 mg/kg Total PAHs in the parent sludge - 382 to 61,218 mg/kg (average of 16,854 mg/kg)
Cost	
Funding Source	

Site Name	Former Industrial Sludge Basin
Site Location	Southeast Texas
Lessons Learned	The decline in contaminant concentrations is likely attributable to rhizodegradation (and not abiotic processes like volatilization or solubilization) since similar declines in concentrations of both mobile and immobile PAHs are believed to have occurred.
Comments	
Primary Contact	
Sources of Information	Olson, P.E., J.S. Fletcher, and P.R. Philp (2001) "Natural Attenuation/Phytoremediation in the Vadose Zone of a Former Industrial Sludge Basin" *Environmental Science and Pollution Research International* . 8 (4): 243-249.

Phytoremediation of Petroleum Hydrocarbons

Site Name	Former John Rogers Tank Farm, Hickam Air Force Base
Site Location	Honolulu, Hawaii
Project Scale	Full-scale
Project Status	Phytoremediation system remains in place, but no additional monitoring is being conducted.
Project Start Date	February 2000
Project Completion Date	
Media Treated	Soil
Site History and Background	The site was formerly used as a petroleum tank farm, but is not currently used.
Site Characterizations	
Contaminants	The site was contaminated with JP-4 jet fuel, various oils, diesel fuel, and aviation gasoline, resulting in measurable PAHs, gasoline range petroleum hydrocarbons, and diesel range petroleum hydrocarbons. Contaminants were primarily associated with a smear zone several ft below the surface.
Initial Contaminant Concentrations	TPH (diesel-range) - 42 to 1,430 mg/kg TPH (gasoline-range) - 84 to 3,300 mg/kg BTEX - 4 mg/kg PAHs - Less than 80 mg/kg (except for naphthalene - averaged 2,600 to 6,200 mg/kg)
Phytotechnology Mechanisms	Rhizodegradation
Vegetation Type	A variety of tropical plant species were evaluated including tropical coral, kiawe, ironwood, bufflegrass, milo, kou, false sandalwood, beach naupaka, oleander, and kiawe.
Planting Descriptions	The site was prepared by clearing existing vegetation, deep ripping, and planting potted material.
Acreage	1.1 acres
Evapotranspiration Rates	Limited data were available for tropical species to be used, and estimated rates for grass vegetation derived from pan evaporation data were used. Potential crop evapotranspiration data was estimated to be 46 inches per year.
Climate	Tropical; Temperature range: 52 to 94F; Elevation: 39 feet; Mean annual precipitation: 22.1"; No frost.
Operation/Maintenance Requirements	
Final Contaminant Concentrations	Final concentrations were generally similar to initial concentrations. The depth to contamination, extreme heterogeneity of contamination, and relatively short time frame between initial and final data collection (2.75 years) limited the potential for significant changes to be observed in the field.
Other Performance Data	
Cost	$580,000, including extensive field studies, greenhouse studies, construction, and monitoring.

Site Name	Former John Rogers Tank Farm, Hickam Air Force Base
Site Location	Honolulu, Hawaii
Funding Source	Funding was provided by the Agriculturally Based Remediation Program (ABRP) administered by the U.S. Army Corps of Engineers. The program was designed to demonstrate agriculturally based remediation technologies relevant to Pacific Island Ecosystems. Additional support was provided by the USAF Environmental Restoration Program for continued maintenance of the site when ABRP funding expired.
Lessons Learned	• Milo and kou rooted to below the brackish groundwater table and into the zone of most concentrated contaminants. • Drip irrigation was much more effective than spray irrigation. • Excavation of small pits to place plants closer to deeper contaminated zones can be very effective, and may actually improve plant growth for these species in this climate. • The same plants as used in greenhouse studies can be successfully established and managed to grow roots deep into coral fill material to influence underlying brackish groundwater and contaminated soil.
Comments	Drip irrigation was especially successful in aiding plant establishment even on very gravelly soils, with 92 percent plant survival.
Primary Contact	Jim Jordahl, Senior Technologist, CH2M HILL, Inc., Des Moines, IA 515-270-2700 x26 Mark Madison, Principle Technologist, CH2M HILL, Inc., Portland, OR 503-235-5022 x4453.
Sources of Information	Emails from Jim Jordahl, 26 July 2006 and 1 August 2006.

Phytoremediation of Petroleum Hydrocarbons

Site Name	Former Refinery
Site Location	Casper, WY
Project Scale	Full-scale
Project Status	Ongoing
Project Start Date	2003
Project Completion Date	
Media Treated	Recovered groundwater
Site History and Background	Former petroleum refinery
Site Characterizations	
Contaminants	BTEX, MTBE, Petroleum hydrocarbons
Initial Contaminant Concentrations	Benzene - 0.2 to 0.8 mg/L BTEX - 0.5 to 5 mg/L MTBE - 1 to 1.6 mg/L Petroleum hydrocarbons - 10 to 40 mg/L
Phytotechnology Mechanisms	Rhizodegradation, Phytodegradation
Vegetation Type	Various wetland species
Planting Descriptions	
Acreage	3 to 4 acres
Evapotranspiration Rates	
Climate	Temperature range: -41 to 102F; Elevation: 5,320 feet; Mean annual precipitation: 12.5"; Growing season: 6/8-9/7.
Operation/Maintenance Requirements	Plant health assessments, fertilizing, irrigation
Final Contaminant Concentrations	
Other Performance Data	
Cost	
Funding Source	BP
Lessons Learned	

Site Name	Former Refinery
Site Location	Casper, WY
Comments	A pilot-scale subsurface flow wetlands was constructed at the site to test whether a constructed wetlands could treat recovered groundwater. The system had four treatment cells packed with sand and operated in upward vertical flow mode. Mean hydraulic detention time was ~1 day. Two of the cells were subjected to forced subsurface aeration using coarse bubble aerators. Various species of willows, reed, bulrush, rush, and dogwood plus sod from a mature wetland which contained roots and shoots of a variety of native species including cattails were used in pilot testing. A volume of 4 gallons per minute was treated. In pilot testing, concentrations were reduced to: Benzene: 0.05 to 0.08 mg/L BTEX: Up to 0.6 mg/L MTBE: 0.8 to 1.2 mg/L Petroleum hydrocarbons: Up to 3 mg/L For benzene, the aerial rate constant was 200 m/yr, which was increased by 50% by aeration.
Primary Contact	David Tsao, BP Group Environmental Management Company, (630) 836-7169, tsaodl@bp.com
Sources of Information	Ferro, A., Kadlec, R., Deschamp, J. (2002) *Constructed Wetland System to Treat Wastewater at the BP Amoco Former Casper Refinery: Pilot Scale Project.* Ninth International Petroleum Environmental Conference, Albuquerque, NM, http://ipec.utulsa.edu/Conf2002/ferro_53.pdf http://www.epareachit.org/ Email from David Tsao, 17 July 2006.

Phytoremediation of Petroleum Hydrocarbons

Site Name	Former Refinery and Tank Farm
Site Location	Cabin Creek, WV
Project Scale	
Project Status	Ongoing
Project Start Date	1999
Project Completion Date	
Media Treated	Soil
Site History and Background	
Site Characterizations	
Contaminants	Petroleum hydrocarbons
Initial Contaminant Concentrations	TPH - More than 5,000 mg/kg
Phytotechnology Mechanisms	
Vegetation Type	Hybrid poplars and grasses
Planting Descriptions	
Acreage	
Evapotranspiration Rates	
Climate	Temperature range: -15 to 104F; Elevation: 951 feet; Mean annual precipitation: 42.5"; Growing season: 5/9-10/5.
Operation/Maintenance Requirements	
Final Contaminant Concentrations	
Other Performance Data	Growth is shown after 3 seasons. Site has been significantly cleaned in 4 years with soil concentrations improving but slower improvement in groundwater concentrations.
Cost	
Funding Source	
Lessons Learned	
Comments	
Primary Contact	Jerald L. Schnoor, Ph.D., P.E., DEE, The University of Iowa, (319) 335-5649, jerald-schnoor@uiowa.edu
Sources of Information	Schnoor, J.L. (2005) *Phytoremediation: From the Molecular to the Field Scale*. Presented to the International Phytotechnologies Conference. 20 April 2005. http://www.cluin.org/phytoconf/proceedings/2005/Plenary_Schnoor.pdf

Phytoremediation of Petroleum Hydrocarbons

Site Name	Fort Wainwright
Site Location	Fairbanks, AK
Project Scale	Full-scale
Project Status	Complete
Project Start Date	1997
Project Completion Date	2002
Media Treated	Soil (ex situ)
Site History and Background	Sources of waste include pesticide manufacturing, use, and storage and drum storage and disposal. Soil was excavated and relocated into lined treatment cells for phytoremediation.
Site Characterizations	Groundwater varies between 5 to 15 feet below ground surface.
Contaminants	Petroleum hydrocarbons, 4,4'-DDD, 4,4'-DDT, Dieldrin
Intiial Contaminant Concentrations	
Phytotechnology Mechanisms	Phytoextraction, Phytodegradation
Vegetation Type	Felt Leaf Willow
Planting Descriptions	Invasive species (felt leaf willow) took over site
Acreage	0.18 acres
Evapotranspiration Rates	
Climate	Temperature range: -62 to 96 F; Mean annual precipitation: 10.9"; Elevation: 599 feet; Growing season: 5/25-8/25.
Operation/Maintenance Requirements	Corn syrup, alcohol amendments, saturated, fertilized, irrigated, fenced.
Final Contaminant Concentrations	Aldrin concentrations decreased but dieldrin concentrations did not.
Other Performance Data	
Cost	
Funding Source	DoD Lead/Federal and State Oversight
Lessons Learned	After treatment, soils from site were deposited in Fort Wainwright landfill rather than an offsite hazardous waste landfill.
Comments	
Primary Contact	Dianne Soderlund, USEPA, soderlund.dianne@epa.gov, (907) 271-3425
Sources of Information	Phytoremediation at Fort Wainwright in Alaska http://www.cluin.org/products/phyto/search/phyto_details.cfm?ProjectID=44 www.epareachit.org

Site Name	Gasoline Release
Site Location	GA
Project Scale	Full-scale
Project Status	
Project Start Date	1999
Project Completion Date	
Media Treated	Soil, Groundwater
Site History and Background	
Site Characterizations	Gasoline was released from a pipeline and flowed into a wetland area on th edge of a creek.
Contaminants	Gasoline
Initial Contaminant Concentrations	
Phytotechnology Mechanisms	Rhizodegradation, Phytodegradation, Phytovolatilization
Vegetation Type	White and black willows, Wooly bull rush, Rush, Native sedge, Cattail
Planting Descriptions	Pilot testing of various plants was conducted for two growing seasons with native sedge found to be effective in remediating shallow soils. In April 2001, 290 bare root willow trees were added in areas with no trees to achieve a four-foot spacing between trees. Deep root planting was used, and aged compost (made of nitrogenous peanut shells and cow manure) was added to the holes before trees were planted. More wetland plants were als added in 2001. 100 trees were also planted in April 2002, but none of these trees survived.
Acreage	
Evapotranspiration Rates	
Climate	Temperature range: -8 to 105F; Mean annual precipitation: 50.8"; Elevation: 977 feet; Growing season: 4/10-10/25.
Operation/Maintenance Requirements	A security fence was installed to prevent animal grazing. No fertilization was required after the initial application at the time of planting. Irrigation was performed as needed in the first growing season, but not needed thereafter.
Final Contaminant Concentrations	BTEX concentrations in soil decreased more than 81% between August 1999 and November 2002. Groundwater concentrations in two wells declined two orders of magnitude since 1997 in two wells but increased by an order of magnitude in a third.
Other Performance Data	In the first growing season, willows grew 1.5 ft per month. Approximately 90% of the planted trees survived in the first growing season, although the highest mortality was in areas with the highest gasoline concentrations. Th lack of irrigation in the second growing season indicates that tree roots had reached the groundwater. Low concentrations of BTEX were found in plan branches and leaves as was benzoic acid (a degradation product).

Site Name	Gasoline Release
Site Location	GA
Cost	
Funding Source	
Lessons Learned	
Comments	
Primary Contact	Walter O'Niell, Planteco Environmental Consultants, woniell@planteco.com
Sources of Information	O'Niell, W.L., and V.A. Nzengung (2004) "In-Situ Bioremediation and Phytoremediation of Contaminated Soils and Water: Three Case Studies" *Environmental Research, Engineering, and Management* . 30(4): 49-54. Planteco Environmental Consultants (2002)*Evaluation of Phytoremediation Performance at the XX Leak Site - 2002 Report.*

Site Name	Grand Forks Air Force Base
Site Location	Grand Forks, North Dakota
Project Scale	Pilot/Field Demonstration
Project Status	Ongoing
Project Start Date	2001
Project Completion Date	
Media Treated	Soil, Groundwater
Site History and Background	The AOC-539 area was the site of a former jet engine testing and maintenance facility that used solvents and other petroleum based liquids during operations. Some of those materials appear to have leaked or spilled onto the ground.
Site Characterizations	Soil consists of sandy loam 0 to 1 feet below ground surface, clay at 4 to 10 ft bgs. Depth to groundwater was 4.3 to 9.4 ft in September 2001, and 2.7 to 5.8 ft in September 2003. Estimated hydraulic gradient prior to site installation was 0.017 feet per foot. In the fall of 2003, gradients ranged from 0.0066 to 0.016 feet per foot. The estimated hydraulic conductivity is 0.371 ft per day.
Contaminants	Gasoline-range organics, trichloroethene, dichloromethane
Initial Contaminant Concentrations in Soil	TPH - 1400 mg/kg Trichloroethene -20 mg/kg
Initial Contaminant Concentrations in Groundwater	TPH - 19,000 ug/L Trichloroethene: 24,000 ug/L
Phytotechnology Mechanisms	Hydraulic Control; Phytodegradation
Vegetation Type	Hybrid Poplar; Eastern Cottonwood; Russian Olive; Carolina Poplar; Imperial Carolina Poplar
Planting Descriptions	All bare root material. Trees planted in 18 inch diameter auger borings 18 to 24 inches deep. Selected trees planted in borings 4 feet deep, but all trees planted at normal depth, i.e., same depth as grown in nursery. Tree spacing is 12 feet between rows, and 6 feet between trees within the row across 0.7 acres.
Acreage	0.7 acres
Evapotranspiration Rates	
Climate	Temperature range: -35 to 106F; Mean annual precipitation: 19.6"; Elevation: 895 feet; Growing season: 5/25-9/12.
Operation/Maintenance Requirements	Mowing, pruning, irrigation, replanting, animal control, insect control
Final Contaminant Concentrations	

Site Name	Grand Forks Air Force Base
Site Location	Grand Forks, North Dakota
Other Performance Data	To date there are no clear trends in contaminant concentrations in groundwater or soil. Groundwater flow patterns are complex and have changed with time and growth of the trees. However, those changes may be influenced by site development that has occurred on the base at adjacent parcels. As of fall 2005, tree evapotranspiration has not developed a groundwater depression.
Cost	Planning/design/implementation through 1 year monitoring: approximately $320,000.
Funding Source	U.S. Air Force
Lessons Learned	Winter injury can be a significant factor in site establishment at northern latitudes, but extent of damage appears to be less with increasing tree age. Winter injury from jackrabbits can be significant. Some damage to poplars was noted in the first year despite tree guards (plastic protective sleeves around stem). Significant damage to some Russian olive trees was noted in the second winter.
Comments	
Primary Contact	Larry Olderbak, Grand Forks AFB Environmental, larry.olderbak@grandforks.af.mil, (701) 747-4183 Al Erickson, CH2M Hill, (414) 847-0303, Al.Erickson@CH2M.com
Sources of Information	Phytoremediation at AOC-539, Grand Forks Air Force Base in North Dakota http://www.cluin.org/products/phyto/search/phyto_details.cfm?ProjectID=18 Email from Larry Olderbak, 26 June 2006.

Site Name	Greiner's Lagoon
Site Location	Ballville Township, OH
Project Scale	Full-scale
Project Status	Ongoing
Project Start Date	2004
Project Completion Date	
Media Treated	Soil, Groundwater
Site History and Background	The site consists of four former lagoons used to store waste oil from nearby industries. In 1987, EPA undertook on-site treatment and discharge of impounded water; stabilization of oils and sludges; covering of all stabilized material with soil; and site regrading. However, some contamination continued to leak from the site, and residents complained of strong petroleum odors even after the removal action was completed.
Site Characterizations	There is approximately 8 to 10 ft of surficial silty sand underlain by roughly 25 ft of silty clay and clay. Limestone or dolomite bedrock is encountered a a depth of 35 ft bgs. Limited amounts of "perched" groundwater occur about four ft bgs in the upper sand unit with more sustainable water yields obtainable from the deeper limestone bedrock.
Contaminants	Acetone, 4-Methyl 2-pentanone, 2-Butanone, Benzene, Phenol, Lead, Cadmium, Chromium, Nickel
Initial Contaminant Concentrations	Acetone - Up to 190 mg/kg and 58,000 ug/L Benzene - Up to 0.160 mg/kg and 63 ug/L 2-Butanone - Up to 2 mg/kg and 1,500 ug/L 4-Methyl 2-pentanone - Up to 150 mg/kg and 30,000 ug/L Toluene - Up to 0.4 mg/kg Bis(2-Ethylhexyl) phthalate - Up to 3.6 mg/kg Phenol - Up to 200 mg/kg and 36,000 ug/L Arsenic - Up to 160 ug/L Chromium - Up to 100 ug/L Lead - Up to 37 ug/L Nickel - Up to 210 ug/L
Phytotechnology Mechanisms	Hydraulic control
Vegetation Type	Poplar trees, switch grass
Planting Descriptions	The construction consists of a foot of clean fill over the stabilized waste oil, with switch grass planted on top of it and poplar trees surrounding the entir site.
Acreage	10 acres
Evapotranspiration Rates	
Climate	
Operation/Maintenance Requirements	

Site Name	Greiner's Lagoon
Site Location	Ballville Township, OH
Final Contaminant Concentrations	
Other Performance Data	Because it was a waste oil site, it had a strong petroleum odor especially on warm days. Odors from the site are now controlled.
Cost	The total cost of the remedy was $719,000. If the stabilized waste oil had been excavated, further stabilized, placed back into the excavation, and a Resource Conservation and Recovery Act (RCRA) Type C cap placed over it, the cost would be $5.6 million.
Funding Source	
Lessons Learned	
Comments	Design began in spring 2004; construction was completed in early 2006.
Primary Contact	Thomas Williams, USEPA, williams.thomas@epa.gov, (312-886-6157)
Sources of Information	Memorandum of "Reports of Significant Developments and Activities Ending on May 5, 2006," from Richard C. Karl, Director, Superfund Division, to Bharat Mathur, Acting Regional Administrator and Norman R. Niedergang, Acting Deputy Regional Administrator, 15 May 2006 http://www.epa.gov/R5Super/significant_actions/2006/060505.pdf#search=%22greiner's%20lagoon%20site%3Aepa.gov%22 ATSDR Health Consultation, Greiner's Lagoon, Fremont, Ohio http://www.atsdr.cdc.gov/HAC/PHA/greinerlagoon/gre_toc.html

Site Name	Hydrocarbon Burn Facility at NASA Kennedy Space Center
Site Location	Cape Canaveral, FL
Project Scale	Full
Project Status	Ongoing
Project Start Date	April 1998
Project Completion Date	
Media Treated	Soil, Groundwater
Site History and Background	
Site Characterizations	Soil consists of medium-coarse sand. Groundwater 1 to 12 ft bgs. Organic chemical spill site, impacted to 12 ft bgs.
Contaminants	1,1-Dichloroethene, cis-1,2-Dichloroethene, Chromium, Total petroleum hydrocarbons, Vinyl chloride, TCE, trans-1,2-Dichloroethene
Initial Contaminant Concentrations in Soil	Chromium - >0.050 mg/kg Total petroleum hydrocarbons - 110-760 mg/kg
Initial Contaminant Concentrations in Groundwater	1,1-Dichloroethene - <1.1-1200 ug/L cis-1,2-Dichloroethene - 65-4800 ug/L Vinyl chloride - <2-456 ug/L Trichloroethene - 0.09-65 mg/L trans-1,2-Dichloroethene - <1.65-110 ug/L
Phytotechnology Mechanisms	Hydraulic Control, Phytodegradation
Vegetation Type	Hybrid Poplar, Understory Grasses
Planting Descriptions	4400 trees and understory grasses
Acreage	3 acres
Evapotranspiration Rate	950L/m^2-year
Climate	Semi-tropical; Temperature range: 25 to 96F; Elevation: 9 feet; mean annual precipitation: 127 centimeters; Growing season: 2/7-12/22
Operation/Maintenance Requirements	Mowing, irrigation
Final Contaminant Concentrations	
Other Performance Data	
Cost	$70,000 for Ecolotree portion
Funding Source	
Lessons Learned	Not able to establish phytoplantation due to competing vegetation (grasses) and drought.
Comments	
Primary Contact	Louis Licht, President, Ecolotree, (319) 665-3547, lou-licht@ecolotree.com Eric Aitchison, Vice President, Ecolotree, (319) 665-3547, eric-aitchison@ecolotree.com

Site Name	Hydrocarbon Burn Facility at NASA Kennedy Space Center
Site Location	Cape Canaveral, FL
Sources of Information	Phytoremediation at the hydrocarbon burn facility at NASA Kennedy Spac Center in Florida http://www.cluin.org/products/phyto/search/phyto_details.cfm?ProjectID=2 5

Phytoremediation of Petroleum Hydrocarbons

Site Name	Indiana Harbors Canal
Site Location	Near Gary, IN
Project Scale	Field demonstration
Project Status	
Project Start Date	May 2002
Project Completion Date	
Media Treated	Soil, groundwater
Site History and Background	The site was on the shores of a shipping channel. The canal was constructed in 1906 and has seen heavy shipping traffic and industry (including manufacturing and petroleum processing) located nearby.
Site Characterizations	Along the Indiana Harbors Canal, there was about 15 cm of a clearly visibly oily layer with loose, well-sorted, relatively permeable sand underneath it. PAH contamination is found in the top 30 cm, and shallow groundwater also has high concentrations of dissolved hydrocarbons. The Lake George Branch of the canal has 1.5 meters of relatively uncontaminated soil over uncontaminated groundwater.
Contaminants	TPH and PAHs
Initial Contaminant Concentrations	TPH - 20,000 to 430,000 mg/kg (mean of 250,000 mg/kg) Total PAHs - mean of 4,100 mg/kg
Phytotechnology Mechanisms	
Vegetation Type	Poplars, Willows
Planting Descriptions	Five replications were planted, four along the east shore of the Indiana Harbors Canal and the fifth as a control in the uncontaminated area of the Lake George Branch. Twenty poplar clones and two willow clones were tested. Some of the poplar clones were planted as both 20- and 60-cm unrooted cuttings, while all other clones were planted only as 20-cm unrooted cuttings. All cuttings had been processed from whips grown for one growing season. Within each replication, there were five rows with 20 trees per row; trees were planted 0.91 m apart. Willow cuttings were planted closest to the water. Cutting were placed in holes filled with clean sand to allow root systems to develop in uncontaminated soils before encountering hydrocarbons contamination. Lower than expected survival was seen in the control replication due to poor site characteristics, preparation, and maintenance.
Acreage	
Evapotranspiration Rates	
Climate	Temperature range: -27 to 104F; Mean annual precipitation: 35.8"; Elevation: 658 feet; Growing season: 4/25-10/22.
Operation/Maintenance Requirements	
Final Contaminant Concentrations	

Site Name	Indiana Harbors Canal
Site Location	Near Gary, IN
Other Performance Data	Examination of two trees after one growing season found five to seven primary lateral roots (from 0.64 to 0.95 cm in diameter) growing up to 1.2 meters laterally into the contaminated soil and down into the groundwater. 97% of 60-cm poplar cuttings survived compared to 62% of 20-cm poplar cuttings and 56% of 20-cm willow cuttings. The overall survival rate was 67%.
Cost	
Funding Source	
Lessons Learned	Commercial clones exhibited greater survival rates than experimental clones. Overall survival rate of 67% was greater than expected given the high levels of TPH contamination encountered.
Comments	
Primary Contact	Dr. Ronald S. Zalesny Jr., Research Plant Geneticist, USDA Forest Service, (715) 362-1132, rzalesny@fs.fed.us
Sources of Information	Zalesny, R.S., Jr., E.O. Bauer, R.B. Hall, J.A. Zalesny, J. Kunzman, C.J. Rog, and D.E. Riemenschneider (2005) "Clonal Variation in Survival and Growth of Hybrid Poplar and Willow in an In Situ Trial On Soils Heavily Contaminated with Petroleum Hydrocarbons" *International Journal of Phytoremediation*. 7(3): 177-197. A Treatability Study for the Phytoremediation of Petroleum-contaminated Sediments. Presentation to U.S. EPA Freshwater Spills Symposium, Cleveland, Ohio, March 19, 2002. http://www.epa.gov/oilspill/pdfs/shalabipresent.pdf

Site Name	Jones Island Confined Disposal Facility - Project 1
Site Location	Milwaukee, WI
Project Scale	Pilot/Field Demonstration
Project Status	Complete
Project Start Date	2001
Project Completion Date	2002
Media Treated	Dredged sediment
Site History and Background	Source of waste is dredged materials from Milwaukee's waterways.
Site Characterizations	Soil consists of brown to black silt.
Contaminants	DRO, PCBs, PAHs
Initial Contaminant Concentrations	DRO - 24 to 440 mg/kg PCBs - 2.0 to 3.6 mg/kg PAHs - 77 to 161 mg/kg
Phytotechnology Mechanisms	Rhizodegradation, Phytodegradation
Vegetation Type	Corn, Sandbar willows, Natural vegetation (in earlier tests, natural vegetation included reed canary grass, sandbar willow, and tall nettle)
Planting Descriptions	Soil was excavated, screened, homogenized, and placed in four plots containing four treatment cells each (one for each of the vegetation types and one for plant suppression). Soil in each of the cells was less than one foot deep. For the corn treatment, a 45-day growing cycle corn was selected. Two growing cycles were completed during each of the growing season. The corn was seeded as “thick as possible” since root mass is considered essential to treatment performance. The seeds were planted usin broadcast spreading techniques. Corn did not germinate in the initial planting and required replanting. For the sandbar willows, a close plant spacing of 1 ft between tree centers was selected.
Acreage	
Evapotranspiration Rates	
Climate	Temperature range: -26 to 103F; Elevation: 672 feet; Mean annual precipitation: 32.9"; Growing season: 5/20-9/26.

Site Name	Jones Island Confined Disposal Facility - Project 1
Site Location	Milwaukee, WI
Operation/Maintenance Requirements	Tilling and weed control (through use of herbicide Roundup) required for plant suppression treatment cells. Corn biomass that was produced was added back into the soil being tested before the next planting. The irrigatio system was used to irrigate the test plots when the tensiometers readings were generally below 30 centibars and/or the plots appeared visibly dry. Consideration was also given to the rain forecast when making the determination to irrigate. The test plots were irrigated on 12 occasions in 2001 and 17 occasions in 2002. Due to the healthy seed bank at the CDF, the willow treatment cells were weeded by hand to reduce competitive growth. In this case, the use of herbicide was not a viable option due to the dense planting of the cuttings and the windy conditions at the site that could spread the herbicide and damage the young trees. Soil attached to the weed roots was removed and returned to the cell.
Final Contaminant Concentrations	None of the four vegetation types achieved a reduction in concentrations of diesel-range organics or PCB Arochlors. Soil samples collected during the final sampling event show that the treatments performed quite similarly when evaluated by the Tukey Test, a standard statistical tool designed to make these types of comparisons. Plant suppression was found to have a final DRO concentration significantly lower (a = 0.10) than natural vegetation. No other significant differences were observed between the various treatments within the DRO, PAH, and PCB data sets. Vegetation growth was assessed two times during 2002. The plant assessments showed vegetation treatments were successfully established. Overall, the shallow depth of the soil in the treatment system probably limited plant growth and root development. The soil depth likely restricted plant nutrient availability and resulted in increased irrigation needs more than would probably be required in a system with a deeper soil profile.
Other Performance Data	All three types of vegetation were established by the second growing seaso Natural vegetation was found to have the highest total root mass in the second growing season followed by corn and then willow, which followed the same order as the reductions in PAH concentrations that season.
Cost	This demonstration treated approximately 142 yds3 of dredged material. Based on this work, estimated costs for remediation of 1,613 yds3 1,613 yds3 (1 acre surface area, 1 foot deep) of dredged material in place are approximately $47,227 and $44,280 for corn and willow treatments, respectively.
Funding Source	

Site Name	Jones Island Confined Disposal Facility - Project 1
Site Location	Milwaukee, WI
Lessons Learned	
Comments	
Primary Contact	Steven Rock, USEPA, (513) 569-7149, rock.steven@epa.gov
Sources of Information	Phytoremediation at Jones Island Confined Disposal Facility in Wisconsin - Project 1 http://cluin.org/products/phyto/search/phyto_details.cfm?ProjectID=20 Dredged Material Reclamation at the Jones Island Confined Disposal Facility Innovative Technology Evaluation Report http://www.epa.gov/ORD/NRMRL/pubs/540r04508/540r04508.pdf

Site Name	Jones Island Confined Disposal Facility - Project 2
Site Location	Milwaukee, WI
Project Scale	Pilot/Field Demonstration
Project Status	Complete
Project Start Date	May 2002
Project Completion Date	September 2004
Media Treated	Soil, Sediment
Site History and Background	Site is a disposal location for dredged sediments from the Milwaukee area.
Site Characterizations	Soil at the site consists of silty clay loam.
Contaminants	PCBs, PAHs, Heavy Metals
Initial Contaminant Concentrations	PAHs - 200 mg/kg
Phytotechnology Mechanisms	Phytoextraction, Phytodegradation
Vegetation Type	Annual Rye (Rye), Black Willow (Willow), Lake Sedge (Carex), Bull Rush (Scirpus), Natural Attenuation (NA), Prairie Cord Grass (Spartina)
Planting Descriptions	From seeds, hand planted.
Acreage	0.06 acre
Evapotranspiration Rates	
Climate	Mostly sunny during the day. Temperature range: -26 to 103F; Elevation: 672 feet; Mean annual precipitation: 32.9"; Growing season: 5/20-9/26.
Operation/Maintenance Requirements	Fertilization, Harvesting, Sampling
Final Contaminant Concentrations	More than 90% of all acenaphthene was removed in all treatments while no more than 13 percent of all indenol(1,2,3-cd)pyrene was removed in all treatments. The unvegetated plot saw a statistically greater reduction in concentrations of six different PAHs.
Other Performance Data	
Cost	Cost is mainly in building the cells and the cost of the plants. Other then that, the main expense was to travel to and from the site and analyzing soil samples.
Funding Source	EPA Hazardous Substance Research Center

Site Name	Jones Island Confined Disposal Facility - Project 2
Site Location	Milwaukee, WI
Lessons Learned	It appears from our results that the high biomass plant treatments impeded the progress of phytoremediation. Our hypothesis as to why this is the case is that the microbes and plants were competing for nutrients, and most of the plant species where perennials and thus would hold the nutrients in their roots and plant tissue. The treatments that did the best, unveg, NA and rye either had little plant cover or had an annual plant or mixture of annual plants that constantly recycled the nutrients back into the soil making those nutrients available to the microbial population. However, all of the degradation rates seen in the experiment were high, so one conclusion that can be drawn is that simply moving the sediments from the anaerobic depth of the CDF onto the surface of the CDF will result in a large amount of PAH loss.
Comments	Publications from this research will be coming out sometime in the next year or so.
Primary Contact	Katy Euliss Smith, University of Massachusetts-Amherst, (413) 545-5979, Katy.Euliss@alumni.purdue.edu
Sources of Information	Phytoremediation at Jones Island Confined Disposal Facility in Wisconsin - Project 2 http://www.cluin.org/products/phyto/search/phyto_details.cfm?ProjectID=21 Email from Katy Euliss Smith, 22 June 2006.

Site Name	Krasnodar
Site Location	Russia
Project Scale	Full scale
Project Status	Ongoing
Project Start Date	2004
Project Completion Date	
Media Treated	Soil
Site History and Background	Controlled release
Site Characterizations	
Contaminants	Naphthalene
Initial Contaminant Concentrations	
Phytotechnology Mechanisms	Rhizodegradation
Vegetation Type	Various species of trees and crops
Planting Descriptions	
Acreage	2 to 3 acres
Evapotranspiration Rates	
Climate	
Operation/Maintenance Requirements	Plant health assessments, fertilizing, irrigation
Final Contaminant Concentrations	
Other Performance Data	
Cost	
Funding Source	BP and U.S. Department of Energy
Lessons Learned	
Comments	
Primary Contact	David Tsao, BP Group Environmental Management Company, (630) 836-7169, tsaodl@bp.com
Sources of Information	Email from David Tsao, 17 July 2006.

Phytoremediation of Petroleum Hydrocarbons

Site Name	Kwinana Refinery
Site Location	Western Australia
Project Scale	Full scale
Project Status	Ongoing
Project Start Date	2000
Project Completion Date	
Media Treated	Soil, groundwater
Site History and Background	Active petroleum refinery
Site Characterizations	
Contaminants	Petroleum hydrocarbons, BTEX
Initial Contaminant Concentrations	
Phytotechnology Mechanisms	Hydraulic control, Rhizodegradation
Vegetation Type	Eucalypts
Planting Descriptions	
Acreage	1 to 2 acres
Evapotranspiration Rates	
Climate	
Operation/Maintenance Requirements	Plant health assessments, fertilizing, irrigation
Final Contaminant Concentrations	
Other Performance Data	
Cost	
Funding Source	BP
Lessons Learned	
Comments	
Primary Contact	David Tsao, BP Group Environmental Management Company, (630) 836-7169, tsaodl@bp.com
Sources of Information	Email from David Tsao, 17 July 2006.

Phytoremediation of Petroleum Hydrocarbons

Site Name	LA Truck Depot
Site Location	Lafayette, LA
Project Scale	Full Scale
Project Status	Complete
Project Start Date	1996
Project Completion Date	June 1997
Media Treated	Soil, Groundwater
Site History and Background	
Site Characterizations	Petroleum hydrocarbons found up to 5 feet below ground surface
Contaminants	Petroleum hydrocarbons (diesel-range) in soil TCE in groundwater
Initial Contaminant Concentrations	Petroleum hydrocarbons in soil - Up to 250 mg/kg Total VOCs in groundwater - Up to 125 ug/L
Phytotechnology Mechanisms	Phytoextraction and Phytovolatilization of TCE, Rhizodegradation
Vegetation Type	Hybrid poplars Willows
Planting Descriptions	Planted at 10 foot intervals.
Acreage	Approximately 100 ft x 100 ft
Evapotranspiration Rates	
Climate	Temperature range: 9 to 102F; Mean annual precipitation: 58.6"; Elevation: 36 feet; Growing season: 3/17 to 11/6.
Operation/Maintenance Requirements	Semi-annual mowing and pruning. No fertilization and no irrigation.
Final Contaminant Concentrations	Petroleum hydrocarbons in soil - Up to 20 mg/kg Total VOCs in groundwater - Up to 75 ug/L
Other Performance Data	There was record rainfall in the first season resulting in loss of some poplars. Those trees were replaced with willows, and nearly 100% survival was seen after that.
Cost	
Funding Source	
Lessons Learned	
Comments	Phytoremediation was implemented primarily to address TCE in groundwater.
Primary Contact	Edward G. Gatliff Ph.D., Applied Natural Sciences, (513) 895-6061, ans@fuse.net
Sources of Information	Applied Natural Sciences - Lafayette, Louisiana - TCE/TPH http://www.treemediation.com/Lafayette.htm Phone interview of Dr. Gatliff, 18 July 2006. www.epareachit.org

Phytoremediation of Petroleum Hydrocarbons

Site Name	Llandarcy Refinery Constructed Treatment Wetland
Site Location	Wales, UK
Project Scale	Pilot scale
Project Status	Complete
Project Start Date	2001
Project Completion Date	2004
Media Treated	Extracted groundwater
Site History and Background	Former petroleum refinery
Site Characterizations	
Contaminants	Petroleum hydrocarbons
Initial Contaminant Concentrations	
Phytotechnology Mechanisms	Biodegradation, Physical/Chemical degradation
Vegetation Type	Reeds
Planting Descriptions	
Acreage	<1 acre
Evapotranspiration Rates	
Climate	
Operation/Maintenance Requirements	Plant health assessments, fertilizing, irrigation
Final Contaminant Concentrations	
Other Performance Data	
Cost	
Funding Source	BP
Lessons Learned	
Comments	
Primary Contact	David Tsao, BP Group Environmental Management Company, (630) 836-7169, tsaodl@bp.com
Sources of Information	Email from David Tsao, 17 July 2006.

Phytoremediation of Petroleum Hydrocarbons

Site Name	McCormick and Baxter Superfund Site
Site Location	Portland, OR
Project Scale	Full
Project Status	Complete
Project Start Dates	March 1997
Project Completion Date	
Media Treated	Soil
Site History and Background	
Site Characterizations	Surface soil is sandy.
Contaminants	Benzo(b)fluoranthene, Chrysene, Fluoranthene, Pentachlorophenol, Pyrene, PAHs
Initial Contaminant Concentrations	Benzo(b)fluoranthene - 4.2 +/- 1.0 mg/kg Chrysene - 11.3 +/- 2.6 mg/kg Fluoranthene - 21.8 +/- 6.1 mg/kg Pentachlorophenol - 80.4 +/- 23.4 mg/kg Pyrene - 33.5 +/- 10.7 mg/kg
Phytotechnology Mechanisms	Rhizodegradation, Phytodegradation
Vegetation Type	Hybrid Poplar, Rye Grass
Planting Descriptions	
Acreage	0.06 acre
Evapotranspiration Rate	
Climate	Temperature range: 6-107F; Mean annual precipitation: 36.3 inches; Elevation: 33 feet; Growing season: 4/26 to 10/18; 65F average summer temperature; 40F average winter temperature; 60% average relative humidity in mid-afternoon; 60% possible sunshine in summer; 14 km/hour average maximum wind speed.
Operation/Maintenance Requirements	Irrigation and fertilization.
Final Contaminant Concentrations	
Other Performance Data	
Cost	U.S. EPA SITE Emerging Technology Program Award ($300,000). Budget includes both greenhouse and field-scale studies for years 1996 and 1997.
Funding Source	
Lessons Learned	Variability in soil containment concentrations may obscure treatment effects. Variability can be reduced by normalizing data for soil moisture and correcting soil containment concentrations by comparison with a recalcitrant soil containment. Pre-mixing.
Comments	
Primary Contact	Ari M. Ferro, Ph.D., Principal Technical Specialist, Phytoremediation, ENSR, (919) 872-6600 x254, aferro@ensr.aecom.com

Site Name	McCormick and Baxter Superfund Site
Site Location	Portland, OR
Sources of Information	Phytoremediation at the McCormick and Baxter Superfund Site in Oregon http://www.cluin.org/products/phyto/search/phyto_details.cfm?ProjectID=119

Site Name	Oil Well Blow-out Site
Site Location	Trecate, Italy
Project Scale	
Project Status	
Project Start Date	April 1998
Project Completion Date	
Media Treated	Soil
Site History and Background	In March 1994, there was a blowout of the oil well at the site. Approximately 25 cm of soil was scraped up and once dried out placed in biopiles for over two years. In April 1998, the soil was returned to the fields.
Site Characterizations	
Contaminants	TPH, PAHs
Initial Contaminant Concentrations	TPH - Average of 3,700 mg/kg
Phytotechnology Mechanisms	Rhizodegradation, Phytoextraction
Vegetation Type	Winter - Fescue, colza, vetch, ryegrass, and landfarming; Summer - Corn, fescue, alfalfa, clover, and landfarming
Planting Descriptions	Plots were ploughed to a depth of 40 cm before seeding of new crops meaning that soil layers that had not previously been involved in phytoremediation and containing higher pollutant concentrations than present at the surface were brought up. Each new growing season started with a state of soil degradation that was different from that present at the end of the preceding season.
Acreage	11 acres
Evapotranspiration Rates	
Climate	
Operation/Maintenance Requirements	
Final Contaminant Concentrations	TPH - Average of 1,000 mg/kg after three growing seasons
Other Performance Data	Over the course of several growing seasons, concentrations of TPH and PAHs in soil were compared on plots with various winter crops, summer crops, natural vegetation, and landfarming. There were no highly significant differences in the impact of crop growth, landfarming, and natural attentuation on hydrocarbon degradation.
Cost	
Funding Source	
Lessons Learned	Phytoremediation appears to produce results at least as good as landfarming. However, phytoremediation offeres protection against erosion maintains proper soil conditions, and is less laborious than landfarming.
Comments	
Primary Contact	

Site Name	Oil Well Blow-out Site
Site Location	Trecate, Italy
Sources of Information	Andreotti, G., N. Plata, A. Porta, and K. Mueller (2001) "Phytoremediation of Hydrocarbon-Polluted Agricultural Soils," In *Phytoremediation, Wetlands, and Sediments* . .A. Leeson, E.A. Foote, M. Katherine Banks, and V.S. Magar (eds.) Batelle Press, Columbus, OH: 41 - 51. Porta, A., N. Filliat, and N. Plata (1999) "Phytotoxicity and Phytoremediation Studies in Soils Polluted by Weathered Oil," In *Phytoremediation and Innovative Strategies for Specialized Remedial Applications* . A. Leeson and B.C. Alleman (eds.) Batelle Press, Columbus, OH: 51 - 56.

Site Name	Oneida Tie Yard Site
Site Location	Oneida, TN
Project Scale	Full-scale
Project Status	Ongoing
Project Start Date	May 1997
Project Completion Date	
Media Treated	Soil, Groundwater
Site History and Background	Site was formerly treatment of railroad ties from the 1953 until 1973.
Site Characterizations	Contaminated soil that was removed in the course of installing trenches for intercepting groundwater was spread across approximately 1/3 of the phytoremediation area. Below that is a surficial aquifer (1 to 2 meters thick) made up of medium sand, sandy clay, and clay. A layer of dense shale is encountered at 3 to 3.5 meters bgs. 0 to 30 cm of creosote as DNAPL is present at the base of the surficial aquifer.
Contaminants	Polycyclic aromatic hydrocarbons (PAHs)
Initial Contaminant Concentrations	Total PAHs - 18,500 ug/L Naphthalene - 17,500 ug/L
Phytotechnology Mechanisms	Rhizodegradation is believed to be the dominant mechanism, but some phytovolatilization also has been shown to occur.
Vegetation Type	Hybrid poplars
Planting Descriptions	1,026 one and two-year old hybrid poplar trees were planted in 13 rows. Another 120 trees were added 11 months later.
Acreage	2 acres
Evapotranspiration Rates	8 liters/day/tree
Climate	Humid; Temperature range: -24 to 102F; Mean annual precipitation: 47.1 inches; Elevation: 981 feet; Growing season: 4/9 to 10/23.
Operation/Maintenance Requirements	Weed and pest control, inspection of trees for damage from insects and disease
Final Contaminant Concentrations	End of 7-year monitoring period (from 1999 to 2005): Total PAHs - 6,400 ug/L Naphthalene - 4,900 ug/L

Site Name	Oneida Tie Yard Site
Site Location	Oneida, TN
Other Performance Data	Trees grew well in areas of PAH contamination, but not in areas where a coal layer was present. No evidence of improved groundwater remediation was seen after two growing seasons. However, a decline in PAH concentrations in groundwater was observed starting in the 3rd and 4th growing seasons (at about the time when tree roots were reaching the water table), and similar declines in PAH concentrations in soil have also been observed. Declines in PAH concentrations were due to remediation of naphthalene and some three-ringed PAHs, but larger PAHs were largely unaffected. After five years of operation, site data indicate a decreasing groundwater gradient, accelerated soil remediation, a transition from anaerobic to aerobic conditions in groundwater with root depth, reduced dissolved PAH concentrations in groundwater, and reduced operation of the existing groundwater interception trench. The estimated time to risk-based closure is 6 years versus the natural attenuation estimate of over 100 years.
Cost	Design - $50,000 Installation - $90,000 Annual operations and maintenance - $35,000
Funding Source	
Lessons Learned	Site characterization efforts failed to discover creosote (DNAPL) source at base of aquifer prior to design and installation of the phyto system. Large gravel prevent direct-push instruments from reaching the base of the aquifer at some locations. DNAPL was later detected underneath approximately 50% of the site. The presence of the DNAPL, a continuous source of contaminants, limited the effectiveness of the phyto system in reducing concentrations in the deeper groundwater and in reducing the remediation timeframe.
Comments	Research was completed in Summer 2005. Currently in closure monitoring.
Primary Contact	Mark A. Widdowson, Virginia Tech, mwiddows@vt.edu Greg Page, ARCADIS G&M, gpage@arcadis-us.com

Site Name	Oneida Tie Yard Site
Site Location	Oneida, TN
Sources of Information	Widdowson, M.A., S. Shearer, R.G. Andersen, and J.T. Novak (2005) "Remediation of Polycyclic Aromatic Hydrocarbon Compounds in Groundwater Using Poplar Trees" Environmental Science and Technology. 39 (6): 1598 - 1605. Novak, J.T., M. Widdowson, M. Elliott, and S. Robinson (2000). "Phytoremediation of a Creosote Contaminated Site - A Field Study" Bioremediation and Phytoremediation of Chlorinated and Recalcitrant Compounds. G. B. Wickramanayake, A.R. Gavaskar, B.C. Alleman, and V.S. Magar (eds.) Batelle Press, Columbus, OH: 493 - 500. Andersen, R.G., E.C. Booth, M. Nelson, L.C. Marr, and J.T. Novak (2005) "Phytovolatilization and Bioremediation of Naphthalene at a Creosote-Contaminated Phytoremediation Site" Proceedings of the Eighth International In Situ and On-Site Bioremediation Symposium. B. C. Alleman and M.E. Kelley (eds.) Batelle Press, Columbus, OH. Emails from Mark Widdowson, 18 and 19 July 2006. Email from Wojciech Jozewicz (ARCADIS) to Ellen Rubin, 29 June 2006. ARCADIS G&M Phytoremediation Demonstration Factsheet - Oneida Tie Yard Site

Site Name	Oregon Pipeline
Site Location	IL
Project Scale	Full scale
Project Status	Ongoing
Project Start Date	2000
Project Completion Date	
Media Treated	Soil
Site History and Background	Active petroleum refinery
Site Characterizations	
Contaminants	BTEX
Initial Contaminant Concentrations	
Phytotechnology Mechanisms	Rhizodegradation, Phytodegradation, Phytovolatilization
Vegetation Type	Alfalfa
Planting Descriptions	
Acreage	22 acres
Evapotranspiration Rates	
Climate	
Operation/Maintenance Requirements	Plant health assessments, fertilization, irrigation
Final Contaminant Concentrations	
Other Performance Data	
Cost	
Funding Source	BP
Lessons Learned	
Comments	
Primary Contact	David Tsao, BP Group Environmental Management Company, (630) 836-7169, tsaodl@bp.com
Sources of Information	Email from David Tsao, 17 July 2006.

Site Name	Phytoremediation Demonstration Plots at the Allen Park Clay Mine Landfill
Site Location	Allen Park, MI
Current/Former Uses of the Site	
Project Scale	Pilot/Field Demonstration
Project Status	
Project Start Date	September 2001
Project Completion Date	
Media Treated	Soil
Site Characterizations	
Contaminants	PAHs
Initial Contaminant Concentrations	PAHs - 130 mg/kg
Phytotechnology Mechanisms	Rhizodegradation
Vegetation Type	In order to promote native habitat restoration concurrent with environmenta detoxification, a plant palette of SE Michigan region native species was developed. Primary greenhouse trials of approximately 50 species identified 18 species of grasses, herbs, and forbs with enhanced PAH phytodegradation rates. Grasses: Big Bluestem, Little Bluestem, Bottlebrush Grass, Prairie Cordgrass Sedges: Sprengel Sedge, Bulrush Herbaceous: Leadplant, New England Aster, Pasture Thistle, Boneset, Joe-PyeWeed, Prairie Smoke, Cardinal Flower, Prairie-dock Shrubs: New Jersey Tea, Common Ninebark, Meadowsweet, Arrowhead Viburnum
Planting Descriptions	Native plants were planted in a field plot containing compost-amended, cok oven soils.
Acreage	
Evapotranspiration Rate	
Climate	Temperature range: -13 to 103F; Mean annual precipitation: 26.6"; Elevation: 619 feet; Growing season: 5/12-10/9.
Operation/Maintenance Requirements	
Final Contaminant Concentrations	

Site Name	Phytoremediation Demonstration Plots at the Allen Park Clay Mine Landfill
Site Location	Allen Park, MI
Other Performance Data	After one growing season, approximately two-thirds of the 19 planted treatments were observed to accelerate PAH biodegradation relative to the unplanted control cells with several species achieving 40-50% reduction in soil PAHs. Most treatments reached 60-65% reduction in soil PAH content after 3 seasons, possibly reaching the biologically treatable limit for this weathered, coking by-product material.
Cost	
Funding Source	
Lessons Learned	Planted treatments were typically more effective at reducing soil PAHs than unplanted treatments. Different plant species had different effects on bacterial biodegrader community. Plants generally enriched broad-range bacterial PAH range bacterial PAH metabolic capabilities. Varied plant community dynamics among species – some more suitable for stable habita restoration
Comments	This work was performed as a demonstration prior to implementation of phytoremediation efforts at the Rouge Manufacturing Complex in Dearborn, MI.
Primary Contact	Clayton L. Rugh, Dept. of Crop and Soil Sciences, Michigan State University, 516 Plant & Soil Sciences Bldg., East Lansing, MI United States, Telephone: (517) 355-0271, E-mail: rugh@msu.edu
Sources of Information	Rugh, C.L., E. Susilawati, D.K. Russell, L.A. Carreira, J.C. Thomas. (2005) *PAH Phytodegradation with Concurrent Habitat Restoration Using Native Plant Species at a Historic Industrial Coke Oven Facility* . From The Third International Phytotechnologies Conference, April 19-22, Atlanta, Georgia. http://cluin.org/phytoconf/proceedings/2005/1A_Rugh.pdf Phytoremediation at a historic rouge manufacturing facility in Michigan http://www.cluin.org/products/phyto/search/phyto_details.cfm?ProjectID=115

Site Name	Privately Owned Scrap Yard
Site Location	Southeastern United States
Current/Former Uses of the Site	Scrap Yard
Project Scale	Full-scale
Project Status	Complete, awaiting closure documents.
Project Start Date	April 2001
Project Completion Date	December 2006
Media Treated	Soil
Site Characterizations	Contaminants were present in the upper three feet of soil across approximately two acres.
Contaminants	PCBs, TPH
Initial Contaminant Concentrations	TPH - 10 to 14,800 mg/kg (average of 4,010 mg/kg) PCBs - 0.77 to 222 mg/kg (average of 65 mg/kg)
Phytotechnology Mechanisms	
Vegetation Type	Red mulberry trees, Bermuda grass
Planting Descriptions	One-foot tall red mulberry seedlings were planted on two-foot centers, and Bermuda grass seed was spread between the trees.
Acreage	2 acres
Evapotranspiration Rates	Hot and humid
Climate	
Operation/Maintenance Requirements	Fertilized and irrigated as needed
Final Contaminant Concentrations	TPH - All below detection limits PCBs - 0 to 8.5 mg/kg (average of 2.2 mg/kg)
Other Performance Data	
Cost	Approximately $140,000
Funding Source	Private
Lessons Learned	Establishing grass and trees at the same time requires a delicate balance. If either gets too far ahead of the other, then one will thrive while the other struggles. It is important to get both so that you have plenty of root density/root contact with contaminants.
Comments	This may be the first successful treatment of PCB contaminated soil, although the exact mechanisms involved are not understood and would require additional research.
Primary Contact	Kelly Hurt, Ph.D., Freelance Consulting Services, Inc., (580) 421-7512, flc33@sbcglobal.net
Sources of Information	Hurt, K. (2005) *Successful Full-Scale Phytoremediation of PCB- and TPH-Contaminated Soil* . From The Third International Phytotechnologies Conference, April 19-22, 2005, Atlanta, Georgia. http://www.cluin.org/phytoconf/proceedings/2005/1B_Hurt.pdf http://www.cluin.org/phytoconf/moreinfo.cfm?id=11

Phytoremediation of Petroleum Hydrocarbons

Site Name	Rochelle Terminal
Site Location	IL
Project Scale	Full scale
Project Status	Ongoing
Project Start Date	2003
Project Completion Date	
Media Treated	Groundwater
Site History and Background	Active petroleum refinery
Site Characterizations	
Contaminants	BTEX, MTBE
Initial Contaminant Concentrations	
Phytotechnology Mechanisms	Phytodegradation, Rhizodegradation, Hydraulic Control, Phytovolatilization
Vegetation Type	Poplars
Planting Descriptions	
Acreage	<1 acre
Evapotranspiration Rates	
Climate	Temperature range: -27 to 104F; Mean annual precipitation: 37.1"; Elevation: 725 feet; Growing season: 5/13-9/25.
Operation/Maintenance Requirements	Plant health assessments, fertilizing, irrigation
Final Contaminant Concentrations	
Other Performance Data	
Cost	
Funding Source	BP
Lessons Learned	
Comments	
Primary Contact	David Tsao, BP Group Environmental Management Company, (630) 836-7169, tsaodl@bp.com
Sources of Information	Email from David Tsao, 17 July 2006.

Site Name	Rouge Manufacturing Complex
Site Location	Dearborn, MI
Project Scale	
Project Status	
Project Start Date	Fall 2002
Project Completion Date	
Media Treated	Soil
Site History and Background	Historic industrial coke oven facility
Site Characterizations	
Contaminants	PAHs
Initial Contaminant Concentrations	
Phytotechnology Mechanisms	Rhizodegradation
Vegetation Type	Large shrubs, short grasses, low shrubs, and tall grasses or trees
Planting Descriptions	24,000 individual plants were planted in 12 plots each with nine sub-plots. Each subplot contained a different combination of type of plant.
Acreage	
Evapotranspiration Rate	
Climate	Temperature range: -13 to 103F; Mean annual precipitation: 26.6"; Elevation: 619 feet; Growing season: 5/12-10/9.
Operation/Maintenance Requirements	
Final Contaminant Concentrations	
Other Performance Data	
Cost	Approximately $8,000 -- $20,000 per acre not including labor costs
Funding Source	
Lessons Learned	
Comments	
Primary Contact	Clayton L. Rugh, Dept. of Crop and Soil Sciences, Michigan State University, 516 Plant & Soil Sciences Bldg., East Lansing, MI United States, Telephone: (517) 355-0271, E-mail: rugh@msu.edu
Sources of Information	Rugh, C.L., E. Susilawati, D.K. Russell, L.A. Carreira, J.C. Thomas. (2005) *PAH Phytodegradation with Concurrent Habitat Restoration Using Native Plant Species at a Historic Industrial Coke Oven Facility* . From The Third International Phytotechnologies Conference, April 19-22, Atlanta, Georgia. http://cluin.org/phytoconf/proceedings/2005/1A_Rugh.pdf

Site Name	RTDF Site A
Site Location	Central CA
Project Scale	Field demonstration
Project Status	Complete
Project Start Date	December 1998
Project Completion Date	June 2000
Media Treated	Soil
Site History and Background	The site is an active petroleum refinery. Source of contaminants are crude oils and API separator sludge from the wastewater treatment system that was deposited in oxidation ponds for a long time.
Site Characterizations	The source material had been in place for several decades and was highly weathered. Contaminants are found up to 12 ft bgs. Groundwater is first encountered 2 to 6 ft bgs.
Contaminants	TPH, PAHs
Initial Contaminant Concentrations	TPH (0 - 15 cm) - Average of 45,535 mg/kg TPH (15 - 45 cm) - Average of 57,444 mg/kg Total Priority PAHs (0 - 15 cm) - Average of 34.3 mg/kg Total Priority PAHs (15 - 45 cm) - Average of 139.8 mg/kg
Phytotechnology Mechanisms	Rhizodegradation, phytostabilization
Vegetation Type	17 plant species including rye, legumes, fescue, and native grasses
Planting Descriptions	All vegetation was removed in all plots prior to new planting. Treatment 1: Rye, legumes, and fescue with perennial ryegrass, blando brown, and small fescue dominant Treatment 2: native California grasses with perennial ryegrass, small fescue, and wild oats dominant Treatment 3: unvegetated
Acreage	12 plots of 25 feet by 30 feet
Evapotranspiration Rates	
Climate	The local climate is Mediterranean with a winter rainy season and main active growth from December through May. Average temperature range - 43 to 72F; Mean annual precipitation - 23"; Growing season - 270 days; No frost.
Operation/Maintenance Requirements	Vegetated plots were fertilized. Glyphosate was used for weeding on unvegetated plot.
Final Contaminant Concentrations	
Other Performance Data	Vegetation grew well, but changes in concentrations from initial to final sampling did not show a difference between treatments.
Cost	
Funding Source	

Site Name	RTDF Site A
Site Location	Central CA
Lessons Learned	At this highly variable site, plants grew well in weathered hydrocarbons, bu there was no clear evidence of a benefit of vegetation for increasing hydrocarbon dissipation. It is possible that the variability patterns obscure the results or a longer period of treatment time is needed.
Comments	
Primary Contact	Peter Kulakow, Ph.D., Kansas State University, (785) 532-7239, kulakow@ksu.edu
Sources of Information	Kulakow, P. (2000) *Annual Report of the RTDF Phytoremediation Action Team - TPH Subgroup Cooperative Field Trials* . March 2000. Kulakow, P. (2006) *Final Report - RTDF Phytoremediation Action Team TPH Subgroup: Cooperative Field Trials* (draft).

Phytoremediation of Petroleum Hydrocarbons

Site Name	RTDF Site B
Site Location	Southwest Ohio
Project Scale	Field demonstration
Project Status	Complete
Project Start Date	April 1999
Project Completion Date	December 2002
Media Treated	Soil
Site History and Background	This site was a land farm at a former petroleum refinery where tank bottoms from the refinery were placed for bioremediation. Source of contaminants are slop oil and API separator sludge.
Site Characterizations	Contaminants are found at approximately 2.5 ft bgs. The source material had already been subjected to a long period of biodegradation. Groundwater is first encountered 50 to 95 ft bgs.
Contaminants	TPH, PAHs
Initial Contaminant Concentrations	TPH (0 - 15 cm) - Average of 13,836 mg/kg TPH (15 - 75 cm) - Average of 12,155 mg/kg Total Priority PAHs (0 - 15 cm) - Average of 52.3 mg/kg Total Priority PAHs (15 - 75 cm) - Average of 64.4 mg/kg
Phytotechnology Mechanisms	Rhizodegradation, Phytostabilization
Vegetation Type	Rye, legume, fescue, hackberry, willow, poplar
Planting Descriptions	Treatment 1: Perennial ryegrass and tall fescue plus goldenrod and orchardgrass in the later years Treatment 2: hackberry and cool-season grasses Treatment 3: willow, poplar, and cool-season grasses Treatment 4: unvegetated The first year after planting was a drought year, and there was low success of tree establishment. Willow and poplar trees were replanted in 2000.
Acreage	16 plots of 35 feet by 35 feet
Evapotranspiration Rates	
Climate	Average temperature range - 20 to 86F; Mean annual precipitation - 41"; Growing season - 175 days; Average first frost - October 15; Average last frost - April 15
Operation/Maintenance Requirements	Vegetated plots were fertilized. Unvegetated plot was weeded by hand.
Final Contaminant Concentrations	
Other Performance Data	After the first drought year, vegetation growth was good with plant cover between 60 - 95%. However, there was no evidence that vegetation enhanced degradation of petroleum hydrocarbons at this site.
Cost	
Funding Source	

Site Name	RTDF Site B
Site Location	Southwest Ohio
Lessons Learned	Field tests of phytoremediation using weathered refinery source material are unlikely to result in clear treatment effects unless other measures are taken to manage the variability.
Comments	Hackberry trees never established, so treatments 1 and 2 were essentially the same.
Primary Contact	Peter Kulakow, Ph.D., Kansas State University, (785) 532-7239, kulakow@ksu.edu
Sources of Information	Kulakow, P. (2000) *Annual Report of the RTDF Phytoremediation Action Team - TPH Subgroup Cooperative Field Trials* . March 2000. Kulakow, P. (2006) *Final Report - RTDF Phytoremediation Action Team TPH Subgroup: Cooperative Field Trials* (draft).

Site Name	RTDF Site C
Site Location	Barrow, AK
Project Scale	Field demonstration
Project Status	Complete
Project Start Dates	June 1999
Project Completion Date	September 2001
Media Treated	Soil
Site History and Background	Sources of waste are a former dry cleaning facility and a former tank farm. Fuel tanks contained diesel fuel, gasoline, Mogas and JP-5 jet fuel. The tanks were removed in 1990, but residual contamination remained from at least two tanks that were known to have leaked.
Site Characterizations	Surface soils are mainly coarse sand and gravel marine beach deposits, but silty in vegetated areas. An estimated 7,000 cubic yards of petroleum contaminated soil present. Soils remain frozen through most of the year, but thaw to a maximum depth of 55 inches in August or September and refreeze by late October. Groundwater occurs only in the thawed zone above the permafrost, and there is no significant flow. Contaminants are found at approximately 3 to 5 feet bgs.
Contaminants	DRO, GRO, PAHs, total residual petroleum (TRP), halogenated aliphatics, phenolics, solvents and inorganic compounds. Also trace-level PCE and daughter products and at the former dry cleaning facility. Lead, BTEX, and PAHs also found at the former tank farm.
Initial Contaminant Concentrations	TPH - 180 to 5,400 mg/kg PAHs - 5.1 to 183 mg/kg Dry Cleaning Facility: DRO - 230 to 810 mg/kg (average 504 mg/kg) GRO - below detection limit to 85 mg/kg (average 18.2 mg/kg) Tank Farm: Total petroleum hydrocarbons - 47 to 9,400 mg/kg DRO - 200 to 260 mg/kg GRO - 838 mg/kg 3 feet below ground TRP - 230 to 250 mg/kg. Lead - 8.1 to 365 mg/kg
Phytotechnology Mechanisms	Rhizodegradation, Phytodegradation
Vegetation Type	Clover, Rye Grass, Fescue

Phytoremediation of Petroleum Hydrocarbons

Site Name	RTDF Site C
Site Location	Barrow, AK
Planting Descriptions	Treatment 1 & 2: 15% Annual Rye Grass, 60-70% Arctared Red Fescue, and 20-25% White Clover Treatment 3 & 4: unvegetated There was minimal soil preparation prior to seeding. Seeds were surface-applied using handheld seeders and then pressed into the soil. The maximu permissible (less than 2,000 mg nitrogen/kg of soil) quantity of standard agricultural fertilizer was added to Treatments 1 and 3.
Acreage	16 plots of 8 feet by 14 feet
Evapotranspiration Rates	
Climate	The area is very cold and dry. Temperature ranges from -19F in February to 40F in July. The average annual precipitation is 4.6 inches. High relative humidity (90 to 95%) in the summer leads to foggy conditions about 25% o the time. Growing season - up to 56 days; Average first frost - anytime; Average last frost - early July
Operation/Maintenance Requirements	Treatments 1 and 3 were fertilized. Unvegetated plots were not weeded.
Final Contaminant Concentrations	Contaminant concentrations were reduced, but there was no clear advantag shown among treatments.
Other Performance Data	Significant plant growth was observed in fertilized areas, and long term cleanup goals are anticipated to be achieved only after continued remediation during future thaw periods.
Cost	Capital cost - $7,250 O&M - $1,400/year Other costs - $6,000/year (includes long-term monitoring, regulatory oversight, compliance testing/analysis, excavation, and disposal of residues) Total cost (based on 10,000 ft^2 treatment area, 2 ft treatment depth, and 10 year period of operation) - $27,250
Funding Source	
Lessons Learned	1. Plants have a positive effect on petroleum depletion relative to either nutrients alone or control treatments. 2. The effect is not uniform across all petroleum fractions. 3. The effect is not seen by standard monitoring techniques. 4. Nutrients alone can have an inhibitory effect on depletion of some petroleum fractions. 5. There are measurable microbial changes that support, and probably drive, the contaminant changes.

Site Name	RTDF Site C
Site Location	Barrow, AK
Comments	Lessons learned during field demonstrations are applicable to applications at a larger scale. Though implementation is relatively straightforward, unfortunately, so are ineffective or incorrect implementation steps. Consideration should be given to altering the monitoring strategy to fit the technology being used; such as timing the sampling event with respect to th status of the system rather than the calendar, selecting an appropriate variable to monitor, and determining how to sample with respect to the selected monitoring variable. The appropriate variable may vary with the degree of "completeness" of the remediation process.
Primary Contact	Dr. C. M. (Mike) Reynolds, ERDC-CRREL, (603) 646-4394, charles.m.reynolds@erdc.usace.army.mil
Sources of Information	Phytoremediation at the former tank farm and former dry cleaning facility i Alaska http://cluin.org/products/phyto/search/phyto_details.cfm?ProjectID=81 Environmental Security Technology Certification Program (2004) *ESTCP Cost and Performance Report: Field Demonstration of Rhizosphere-Enhanced Treatment of Organics-Contaminated Soils on Native American Lands with Application to Northern FUD Sites.* Reynolds, C.M., ERDC-CRREL, Hanover, NH. ERDC/CRREL/LR-04-19, http://costperformance.org/pdf/20050614_367.pdf EPA. Federal Remediation Technologies Roundtable. (2005) *Technology Cost and Performance Report Summary: Rhizosphere-Enhanced Bioremediation of Petroleum, Oil and Lubricant (POL)-Contaminated Soils at Three Sites in Alaska.* http://costperformance.org/profile.cfm?ID=376&CaseID=376 Kulakow, P. (2000) Annual Report of the RTDF Phytoremediation Action Team - TPH Subgroup Cooperative Field Trials. March 2000. Kulakow, P. (2006) Final Report - RTDF Phytoremediation Action Team TPH Subgroup: Cooperative Field Trials (draft).

Site Name	RTDF Site D
Site Location	Galena, Alaska
Project Scale	Field Demonstration
Project Status	Complete
Project Start Dates	September 1998
Project Completion Date	September 1999
Media Treated	Soil
Site History and Background	This site is a former long-range radar site, located approximately six miles east of the interior town of Galena, Alaska. Operational from 1952 to 1984, Campion served as a communications facility supporting a high-frequency radio system, WACS, and a satellite communication system at various time during its operation. The facility was deactivated in 1984 and demolished in 1986.
Site Characterizations	The waste source is presumed to be from storage of heating oil and aviation fuels. The facility operated a tank farm that was serviced by underground fuel pipelines. Groundwater is first encountered 3 to 4 ft bgs. Contaminants are found at 3 ft bgs and deeper.
Contaminants	DRO and GRO
Initial Contaminant Concentrations	DRO - 36 to 75,000 mg/kg GRO - 59 to 7,500 mg/kg BTEX - 0.2 to 33.9 mg/kg
Phytotechnology Mechanisms	Rhizodegradation, Phytodegradation
Vegetation Type	Clover, Rye Grass, Fescue
Planting Descriptions	Treatment 1 & 2: 10-15% Annual Rye Grass, 60-70% Arctared Red Fescue, and 20-25% White Clover Treatment 3 & 4: unvegetated There was minimal soil preparation prior to seeding. Seeds were surface-applied using handheld seeders and then pressed into the soil. The maximum permissible (less than 2,000 mg nitrogen/kg of soil) quantity of standard agricultural fertilizer was added to Treatments 1 and 3.
Acreage	16 plots of 15 feet by 25 feet
Evapotranspiration Rates	
Climate	This site is interior Alaska and is cold and somewhat dry. Precipitation and surface winds are generally light with a mean annual precipitation of about 12 inches. Temperature variations between winter and summer can be extreme with a mean annual temperature of 27 F. Growing season - 100 days; Average first frost - September 1; Average last frost - May 1
Operation/Maintenance Requirements	Treatments 1 and 3 were fertilized. Unvegetated plots were weeded by hand.
Final Contaminant Concentrations	Contaminant concentrations were reduced, but there was no evidence of increased contaminant degradation with the presence of plants.

Site Name	RTDF Site D
Site Location	Galena, Alaska
Other Performance Data	Significant plant growth was observed in fertilized areas, and long term cleanup goals are anticipated to be achieved only after continued remediation during future thaw periods.
Cost	Capital cost - $7,250 O&M - $1,400/year Other costs - $6,000/year (includes long-term monitoring, regulatory oversight, compliance testing/analysis, excavation, and disposal of residues) Total cost (based on 10,000 ft^2 treatment area, 2 ft treatment depth, and 10 year period of operation) - $27,250
Funding Source	
Lessons Learned	1. Plants have a positive effect on petroleum depletion relative to either nutrients alone or control treatments. 2. The effect is not uniform across all petroleum fractions. 3. The effect is not seen by standard monitoring techniques. 4. Nutrients alone can have an inhibitory effect on depletion of some petroleum fractions. 5. There are measurable microbial changes that support, and probably drive, the contaminant changes.
Comments	Lessons learned during field demonstrations are applicable to applications at a larger scale. Though implementation is relatively straightforward, unfortunately, so are ineffective or incorrect implementation steps. Consideration should be given to altering the monitoring strategy to fit the technology being used; such as timing the sampling event with respect to th status of the system rather than the calendar, selecting an appropriate variable to monitor, and determining how to sample with respect to the selected monitoring variable. The appropriate variable may vary with the degree of "completeness" of the remediation process.
Primary Contact	Dr. C. M. (Mike) Reynolds, ERDC-CRREL, (603) 646-4394, charles.m.reynolds@erdc.usace.army.mil

Site Name	RTDF Site D
Site Location	Galena, Alaska
Sources of Information	Phytoremediation at Galena/Campion Site (former Air Force station) in Alaska http://cluin.org/products/phyto/search/phyto_details.cfm?ProjectID=85 Environmental Security Technology Certification Program (2004) *ESTCP Cost and Performance Report: Field Demonstration of Rhizosphere-Enhanced Treatment of Organics-Contaminated Soils on Native American Lands with Application to Northern FUD Sites* . Reynolds, C.M., ERDC-CRREL, Hanover, NH. ERDC/CRREL/LR-04-19, http://costperformance.org/pdf/20050614_367.pdf EPA. Federal Remediation Technologies Roundtable. (2005) *Technology Cost and Performance Report Summary: Rhizosphere-Enhanced Bioremediation of Petroleum, Oil and Lubricant (POL)-Contaminated Soils at Three Sites in Alaska* . http://costperformance.org/profile.cfm?ID=376&CaseID=376 Kulakow, P. (2000) Annual Report of the RTDF Phytoremediation Action Team - TPH Subgroup Cooperative Field Trials. March 2000. Kulakow, P. (2006) Final Report - RTDF Phytoremediation Action Team TPH Subgroup: Cooperative Field Trials (draft).

Phytoremediation of Petroleum Hydrocarbons

Site Name	Annette Island Site
Site Location	Metlakatla, Alaska
Project Scale	Field demonstration
Project Status	Complete
Project Start Dates	September 1998
Project Completion Date	May 2001
Media Treated	Soil
Site History and Background	Currently owned by the Metlakatla Indian Community, the site is a former U.S. Army Air Force landing field established in 1940 under a use permit granted by the Department of the Interior. Approximately 35 fuel tanks witl a combined capacity of 100 million gallons were installed at various points on the island.
Site Characterizations	Source of contaminants are refined oil products including motor oil and diesel presumed to be from operation of the tank farm. Groundwater is firs encountered less than 0.7 feet bgs.
Contaminants	Fuel-related contaminants including diesel- and gasoline-range organics.
Initial Contaminant Concentrations	TPH - Up to 2,130 mg/kg BTEX - Up to 44.6 mg/kg
Phytotechnology Mechanisms	Rhizodegradation, Phytodegradation
Vegetation Type	Clover, Rye Grass, Fescue
Planting Descriptions	Treatment 1 & 2: 10-15% Annual Rye Grass, 60-70% Arctared Red Fescue, and 20-25% White Clover Treatment 3 & 4: unvegetated There was minimal soil preparation prior to seeding. Seeds were surface-applied using handheld seeders and then pressed into the soil. The maximui permissible (less than 2,000 mg nitrogen/kg of soil) quantity of standard agricultural fertilizer was added to Treatments 1 and 3.
Acreage	16 plots of 7 feet by 14 feet
Evapotranspiration Rates	
Climate	The climate is wet and relatively mild by cold-region standards. The area receives a high annual precipitation averaging 155 inches/year, with an average temperature of 45.9F. Growing season - 180 days; Average first frost - October 15; Average last frost - April 1
Operation/Maintenance Requirements	Treatments 1 and 3 were fertilized. Unvegetated plots were not weeded.
Final Contaminant Concentrations	All treatments showed declines in TPH concentrations, but no difference was seen between vegetated and unvegetated treatments.
Other Performance Data	Significant plant growth was observed in fertilized areas, and long term cleanup goals are anticipated to be achieved only after continued remediation during future thaw periods. Fertilizer appeared to enhance degradation.

Site Name	Annette Island Site
Site Location	Metlakatla, Alaska
Cost	Capital cost - $7,250; Operation and maintenance - $1,400 per year Other costs - $6,000 per year (includes long-term monitoring, regulatory oversight, compliance testing/analysis, excavation, and disposal of residues) Total cost (based on a 10,000-ft^2 treatment area, 2-ft treatment depth, and 10 year period of operation) - $27,250
Funding Source	
Lessons Learned	1. Plants have a positive effect on petroleum depletion relative to either nutrients alone or control treatments. 2. The effect is not uniform across all petroleum fractions. 3. The effect is not seen by standard monitoring techniques. 4. Nutrients alone can have an inhibitory effect on depletion of some petroleum fractions. 5. There are measurable microbial changes that support, and probably drive, the contaminant changes.
Comments	Lessons learned during field demonstrations are applicable to applications at a larger scale. Though implementation is relatively straightforward, unfortunately, so are ineffective or incorrect implementation steps. Consideration should be given to altering the monitoring strategy to fit the technology being used; such as timing the sampling event with respect to th status of the system rather than the calendar, selecting an appropriate variable to monitor, and determining how to sample with respect to the selected monitoring variable. The appropriate variable may vary with the degree of "completeness" of the remediation process.
Primary Contact	Dr. C. M. (Mike) Reynolds, ERDC-CRREL, (603) 646-4394, charles.m.reynolds@erdc.usace.army.mil

Site Name	Annette Island Site
Site Location	Metlakatla, Alaska
Sources of Information	Phytoremediation at the Annette Island Site, Former US Army Air Force Landing Field in Alaska http://cluin.org/products/phyto/search/phyto_details.cfm?ProjectID=80 Environmental Security Technology Certification Program (2004) *ESTCP Cost and Performance Report: Field Demonstration of Rhizosphere-Enhanced Treatment of Organics-Contaminated Soils on Native American Lands with Application to Northern FUD Sites* . Reynolds, C.M., ERDC-CRREL, Hanover, NH. ERDC/CRREL/LR-04-19, http://costperformance.org/pdf/20050614_367.pdf EPA. Federal Remediation Technologies Roundtable. 2005. *Technology Cost and Performance Report Summary: Rhizosphere-Enhanced Bioremediation of Petroleum, Oil and Lubricant (POL)-Contaminated Soils at Three Sites in Alaska* . http://costperformance.org/profile.cfm?ID=376&CaseID=376 Kulakow, P. (2000) Annual Report of the RTDF Phytoremediation Action Team - TPH Subgroup Cooperative Field Trials. March 2000. Kulakow, P. (2006) Final Report - RTDF Phytoremediation Action Team TPH Subgroup: Cooperative Field Trials (draft).

Phytoremediation of Petroleum Hydrocarbons

Site Name	RTDF Site F
Site Location	Utica, NY
Project Scale	Field demonstration
Project Status	Complete
Project Start Date	June 1999
Project Completion Date	2002
Media Treated	Soil
Site History and Background	The site is a former manufactured gas plant that operated from 1845 to the mid-1950s.
Site Characterizations	Groundwater is first encountered from 1 to 8 ft bgs. Depth of contamination is approximately 20 ft bgs.
Contaminants	TPH, PAHs
Initial Contaminant Concentrations	TPH (0 - 20 cm) - Average of 1,429 mg/kg TPH (20 - 40 cm) - Average of 649 mg/kg Total Priority PAHs (0 - 20 cm) - Average of 361.4 mg/kg Total Priority PAHs (20 - 40 cm) - Average of 123.1 mg/kg
Phytotechnology Mechanisms	Rhizodegradation, Phytostabilization
Vegetation Type	White clover, boreal red fescue, Kentucky bluegrass, annual rye, perennial rye, willow, poplar, volunteer revegetation
Planting Descriptions	Treatment 1: 16% white clover, 36% boreal red fescue, 36% Kentucky bluegrass, 6% annual rye, 6% perennial rye Treatment 2: Willow, poplar Treatment 3: Volunteer revegetation Treatment 4: Unvegetated
Acreage	16 plots of 20 feet by 20 feet
Evapotranspiration Rates	
Climate	Average temperature range - 13 to 80 F; Mean annual precipitation - 43"; Growing season - 175 days; Average first frost - October 19; Average last frost - April 27
Operation/Maintenance Requirements	None of the plots were fertilized. Unvegetated plot was weeded with glyphosate.
Final Contaminant Concentrations	The concentrations of PAHs in surface soil declined, and there was trend showing that vegetated treatments were declining more than the unvegetated treatment, but it was not significant at all time points. Concentrations of PAHs in deeper soil did not change during three growing seasons.
Other Performance Data	Plants grew well with good aboveground and root biomass and coverage of the ground surface. The grass/legume mixture and the willow/poplar treatment showed very high vegetation cover while the natural revegetation treatment took several years to establish full coverage.
Cost	
Funding Source	

Site Name	RTDF Site F
Site Location	Utica, NY
Lessons Learned	Vegetation can grow successfully on former manufactured gas plant sites and is probably most useful for stabilizing contamination at similar sites. A grass/legume mixture is likely to produce roots more rapidly than tree or volunteer plantings. Tree plantings are likely to produce deeper roots than herbaceous plantings. Natural revegetation may take several years to establish. Root and mass density is likely to vary from season to season.
Comments	
Primary Contact	Peter Kulakow, Ph.D., Kansas State University, (785) 532-7239, kulakow@ksu.edu
Sources of Information	Kulakow, P. (2000) *Annual Report of the RTDF Phytoremediation Action Team - TPH Subgroup Cooperative Field Trials* . March 2000. Kulakow, P. (2006) *Final Report - RTDF Phytoremediation Action Team TPH Subgroup: Cooperative Field Trials* (draft).

Site Name	RTDF Site G
Site Location	Fort Riley, KS
Project Scale	Field demonstration
Project Status	Complete
Project Start Date	September 1999
Project Completion Date	2002
Media Treated	Soil
Site History and Background	Source of contamination is sediments from vehicle repair operations accumulated in a lagoon.
Site Characterizations	The sediment is a clay loam with 18 - 26% sand. Soil pH is 6.8 to 8.2, and soil salinity is low. Depth of contamination is approximately 0 - 2 ft bgs. The contaminated sediments had not been subjected to significant prior biodegradation due to being submerged in a lagoon.
Contaminants	TPH (motor oils and lubricants), PAHs
Initial Contaminant Concentrations	TPH (0 - 15 cm) - Average of 14,704 mg/kg TPH (15 - 45 cm) - Average of 12,762 mg/kg Total Priority PAHs (0 - 15 cm) - Average of 12.4 mg/kg Total Priority PAHs (15 - 45 cm) - Average of 16.8 mg/kg
Phytotechnology Mechanisms	Rhizodegradation, Phytostabilization
Vegetation Type	Western wheatgrass, sweetclover, tall fescue, switchgrass
Planting Descriptions	Treatment 1: 10 - 15% western wheatgrass, 20 - 25% sweetclover, and 60 - 70% tall fescue Treatment 2: switchgrass Treatment 3: unvegetated
Acreage	12 plots of 20 feet by 20 feet
Evapotranspiration Rates	
Climate	Average temperature range - 17 to 91F; Mean annual precipitation - 33" (but the climate was drier than normal during the trial period); Growing season - 180 days; Average first frost - October 15; Average last frost - April 15
Operation/Maintenance Requirements	Vegetated plots were fertilized twice a year with 50 pounds nitrogen per acre and 25 pounds phosphorus per acre. Unvegetated plots were weeded with glyphosate.
Final Contaminant Concentrations	Vegetation treatments with added fertilizer resulted in lower concentrations of TPH and PAHs compared to unvegetated plots. Reductions in hydrocarbons concentrations were slower at lower soil depths, but the difference between vegetated and unvegetated treatments were larger for deeper soil samples.
Other Performance Data	Vegetation established well; however, a high proportion of the plant cover was volunteer species including cheatgrass. Plant root growth and aboveground biomass was generally less than at other RTDF sites. Sufficient reductions in hydrocarbons were likely achieved in one year to satisfy potential risk based cleanup requirements.
Cost	

Site Name	RTDF Site G
Site Location	Fort Riley, KS
Funding Source	
Lessons Learned	The biomarker hopane was useful for normalization of petroleum hydrocarbons data to reduce experimental error and provide better discrimination of treatment effects.
Comments	
Primary Contact	Peter Kulakow, Ph.D., Kansas State University, (785) 532-7239, kulakow@ksu.edu
Sources of Information	Kulakow, P. (2000) *Annual Report of the RTDF Phytoremediation Action Team - TPH Subgroup Cooperative Field Trials* . March 2000. Kulakow, P. (2006) *Final Report - RTDF Phytoremediation Action Team TPH Subgroup: Cooperative Field Trials* (draft).

Site Name	RTDF Site H
Site Location	Providence, RI
Project Scale	Field demonstration
Project Status	Complete
Project Start Date	May 2001
Project Completion Date	2003
Media Treated	Soil
Site History and Background	The site is a former refined petroleum product distribution facility. Source of contamination is released refined petroleum products (including PRS1 and PRS6) and refinery waste.
Site Characterizations	Groundwater is first encountered approximately 25 to 45 ft bgs. Contamination is found up to 15 ft bgs.
Contaminants	TPH, PAHs
Initial Contaminant Concentrations	
Phytotechnology Mechanisms	Rhizodegradation, Phytostabilization
Vegetation Type	Alfalfa, volunteer grasses and forb species
Planting Descriptions	Treatment 1: 10 - 15% rye, 20 - 25% legume, 60 - 70% fescue Treatment 2 & 3: unvegetated
Acreage	
Evapotranspiration Rates	
Climate	Average temperature range - 19 to 82F; Mean annual precipitation - 37"; Growing season - 175 days; Average first frost - October 16; Average last frost - April 26
Operation/Maintenance Requirements	Treatments 1 and 3 were fertilized.
Final Contaminant Concentrations	November 2002 - TPH (0 - 15 cm) - Mean of 1,227 mg/kg TPH (15 - 45 cm) - Mean of 1,922 mg/kg
Other Performance Data	High variability in data prevented detecting any trends in concentrations or differences among treatments. Vegetation grew well with generally more than 90% cover in Treatment 1.
Cost	
Funding Source	
Lessons Learned	
Comments	
Primary Contact	David Tsao, BP Group Environmental Management Company, (630) 836-7169, tsaodl@bp.com
Sources of Information	Kulakow, P. (2000) *Annual Report of the RTDF Phytoremediation Action Team - TPH Subgroup Cooperative Field Trials*. March 2000. Kulakow, P. (2006) *Final Report - RTDF Phytoremediation Action Team TPH Subgroup: Cooperative Field Trials* (draft).

Phytoremediation of Petroleum Hydrocarbons

Site Name	RTDF Site I
Site Location	Southern Illinois
Project Scale	Field demonstration
Project Status	Complete
Project Start Date	November 2000
Project Completion Date	October 2003
Media Treated	Soil
Site History and Background	The site is in a tank farm in a former petroleum refinery. Source of contamination is refined petroleum products (including PRS1 and PRS6) and refinery waste.
Site Characterizations	Groundwater is first encountered approximately 10 feet below ground surface (bgs). Depth of contamination is less than 2 feet bgs.
Contaminants	TPH, PAHs
Initial Contaminant Concentrations	TPH - 180 to 96,000 mg/kg Total PAHs - 1.2 to 5,784 mg/kg
Phytotechnology Mechanisms	Rhizodegradation, Phytostabilization
Vegetation Type	Rye, legume, tall fescue, native prairie grasses and forbs
Planting Descriptions	Treatment 1: 10 - 15% rye, 20 - 25% legume, 60 - 70% tall fescue Treatment 2: Native prairie grasses and forbs Treatment 3 & 4: Unvegetated
Acreage	
Evapotranspiration Rates	
Climate	Average temperature range - 18 to 88F; Mean annual precipitation - 46"; Growing season - 196 days; Average first frost - October 27; Average last frost - April 13
Operation/Maintenance Requirements	Treatments 1, 2, and 3 were fertilized. The unplanted treatments were maintained with the herbicide glyphosate.
Final Contaminant Concentrations	Treatment means did not show consistent decreasing trends to suggest contaminant dissipation was occurring or that there were differences between treatments.
Other Performance Data	Vegetation grew well at the site, but the established plant species composition was primarily volunteer species rather than planted species.
Cost	
Funding Source	
Lessons Learned	There was no evidence that vegetation enhanced degradation of petroleum hydrocarbons at the site. Additional management would be needed to establish specific plant communities from seed.
Comments	
Primary Contact	David Tsao, BP Group Environmental Management Company, (630) 836-7169, tsaodl@bp.com

Site Name	RTDF Site I
Site Location	Southern Illinois
Sources of Information	Kulakow, P. (2000) *Annual Report of the RTDF Phytoremediation Action Team - TPH Subgroup Cooperative Field Trials* . March 2000. Kulakow, P. (2006) *Final Report - RTDF Phytoremediation Action Team TPH Subgroup: Cooperative Field Trials* (draft).

Phytoremediation of Petroleum Hydrocarbons

Site Name	RTDF Site J
Site Location	El Dorado, AR
Project Scale	Field demonstration
Project Status	Complete
Project Start Date	October 1999
Project Completion Date	October 2001
Media Treated	Soil
Site History and Background	The site is an oil storage/separation facility. Source of contamination was a crude oil spill that occurred in 1997.
Site Characterizations	
Contaminants	TPH, PAHs
Initial Contaminant Concentrations	TPH - 3,000 to 24,000 mg/kg
Phytotechnology Mechanisms	Rhizodegradation, Phytostabilization
Vegetation Type	Rye, legume, fescue, Bermuda grass
Planting Descriptions	Treatment 1: Tall fescue, ryegrass Treatment 2: Bermuda grass, tall fescue Treatment 3: Unvegetated Vegetated plots were fertilized with inorganic fertilizer and dolmitic lime at 1,600 kg/ha and 1,450 kg/ha respectively at planting.
Acreage	12 plots of 400 square feet
Evapotranspiration Rates	
Climate	Average temperature range - 30 to 92F; Mean annual precipitation - 53"; Growing season - 180 days; Average first frost - October 22; Average last frost - April 16
Operation/Maintenance Requirements	Vegetated plots were fertilized with 320 kg/ha of inorganic fertilizer 6, 17, and 21 months after planting. Unvegetated plots were weeded with glyphosate.
Final Contaminant Concentrations	Concentrations of TPH and PAHs declined, and one sampling method showed that concentrations in the vegetated treatments were found to be significantly lower than the unvegetated treatment. Greater decreases in PAH concentrations were observed for PAHs with fewer rings and less alkylation.
Other Performance Data	Tall fescue, Bermuda grass, and ryegrass produced good cover at the site.
Cost	
Funding Source	
Lessons Learned	The large decline in hydrocarbons concentration showed the petroleum source had residual degradability, and phytoremediation with fertilization appeared to be an effective treatment method.
Comments	
Primary Contact	Peter Kulakow, Ph.D., Kansas State University, (785) 532-7239, kulakow@ksu.edu

Site Name	RTDF Site J
Site Location	El Dorado, AR
Sources of Information	Kulakow, P. (2000) *Annual Report of the RTDF Phytoremediation Action Team - TPH Subgroup Cooperative Field Trials* . March 2000. Kulakow, P. (2006) *Final Report - RTDF Phytoremediation Action Team TPH Subgroup: Cooperative Field Trials* (draft).

Phytoremediation of Petroleum Hydrocarbons

Site Name	RTDF Site K
Site Location	Indiana
Project Scale	Field demonstration
Project Status	
Project Start Date	May 1999
Project Completion Date	Spring 2002
Media Treated	
Site History and Background	The site is a former manufactured gas plant.
Site Characterizations	Groundwater is first encountered at approximately three feet below ground surface (bgs). Contamination is found from two to ten feet bgs.
Contaminants	PAHs
Initial Contaminant Concentrations	Total Priority PAHs (0 - 60 cm) - Average of 781 mg/kg Total Priority PAHs (60 - 120 cm) - Average of 1,515.2 mg/kg
Phytotechnology Mechanisms	Rhizodegradation, Phytostabilization
Vegetation Type	Willow, poplar
Planting Descriptions	Treatment 1: Willow, poplar Treatment 2: Unvegetated 60 poplar trees were planted on each 7.2 m by 7.2 m plot.
Acreage	8 plots of 24 feet by 24 feet
Evapotranspiration Rates	
Climate	Average temperature range - 16.7 to 86 F; Mean annual precipitation - 45 inches; Growing season - 175 days; Average first frost - October 15; Average last frost - April 15
Operation/Maintenance Requirements	Irrigation was supplied as needed, but no fertilizer was applied to the phytoremediation treatment.
Final Contaminant Concentrations	There was no clear evidence of reductions in PAH concentrations in the phytoremediation plots during a three year period.
Other Performance Data	Poplar tree growth was excellent. Although there was some variation in th size of trees across the site, the trees were generally healthy with little or no mortality except for one section of the site that was influenced by cyanide contamination. Root samples taken from the top 30 cm of soil showed goo tree root development.
Cost	
Funding Source	
Lessons Learned	

Site Name	RTDF Site K
Site Location	Indiana
Comments	The main objective of this project was to compare natural attenuation with three active treatment technologies for their ability to degrade PAHs in soil The treatments included two ex-situ treatments, biopile/composting and lan treatment, and two in-situ treatments, natural attenuation and phytoremediation. The ex-situ treatments were run for 1 year each and the in-situ treatments were run for 3 years each. The experimental design did not follow the RTDF protocol
Primary Contact	Peter Kulakow, Ph.D., Kansas State University, (785) 532-7239, kulakow@ksu.edu
Sources of Information	Kulakow, P. (2000) *Annual Report of the RTDF Phytoremediation Action Team - TPH Subgroup Cooperative Field Trials* . March 2000. Kulakow, P. (2006) *Final Report - RTDF Phytoremediation Action Team TPH Subgroup: Cooperative Field Trials* (draft).

Site Name	Solvent Spill Site
Site Location	Central Iowa
Project Scale	Full-scale
Project Status	Ongoing
Project Start Date	May 2002
Project Completion Date	
Media Treated	Groundwater
Site History and Background	
Site Characterizations	Groundwater is located 11 to 14 ft bgs. Soil is fine and medium grain sands and then tight clay 13 to 21 ft bgs.
Contaminants	PCE, BTEX
Initial Contaminant Concentrations	PCE - More than 20,000 ug/L
Phytotechnology Mechanisms	
Vegetation Type	Poplar trees and understory grasses
Planting Descriptions	A total of 665 trees were planted in four different areas at the site.
Acreage	
Evapotranspiration Rates	
Climate	Temperature range: -24 to 108 F; Elevation: 968 feet; Mean annual precipitation: 33.1"; Growing season: 5/9-9/21.
Operation/Maintenance Requirements	
Final Contaminant Concentrations	
Other Performance Data	PCE, 1,1,1-trichloroethane, toluene, and xylenes are all trending downward in the area of highest initial concentrations. More than 93% of the trees survived, but some phytotoxicity was observed in area of highest PCE concentrations.
Cost	
Funding Source	
Lessons Learned	
Comments	
Primary Contact	Louis Licht, Ecolotree, louis-licht@ecolotree.com
Sources of Information	Just, Craig L. (2005) "*Using Hybrid Poplar to Meet 'No Further Action' Criteria for an Organic Solvent Site* ," From The Third International Phytotechnologies Conference, April 19-22, Atlanta, Georgia, http://www.cluin.org/phytoconf/proceedings/2005/2B_Just.pdf

Site Name	Solvent Recovery Service New England (SRSNE) Superfund Site
Site Location	Southington, CT
Project Scale	Pilot/Field Demonstration
Project Status	Ongoing
Project Start Date	May 1998
Project Completion Date	2030
Media Treated	Soil, Groundwater
Site History and Background	The site was used to reclaim spent industrial solvents from 1955 to 1991.
Site Characterizations	Groundwater is 3 feet below ground surface. Contamination is found from 3 ft bgs to bedrock (at 30 ft bgs).
Contaminants	1,1,1-Trichloroethane, 1,1-Dichloroethane, Toluene, 1,1-Dichloroethene, Vinyl chloride, PCBs
Initial Contaminant Concentrations	1,1,1-Trichloroethane - 0.1 to 35 mg/kg 1,1-Dichloroethane - 0.1 to 25 mg/kg Toluene - 0.1 to 40 mg/kg
Phytotechnology Mechanisms	Hydraulic Control, Phytodegradation, Rhizodegradation, Phytovolatilization
Vegetation Type	Hybrid Poplar, White Willow, Eastern White Pine, and Native Species (Pin Oak, Sweet Gum, Silver Maple, River Birch, Tulip Tree, Eastern Red Bud)
Planting Descriptions	10-12 four- to five-foot deep trenches were dug, planted with approximately 1,000 bare-root hybrid poplar saplings, and backfilled with a sand/compost mixture. The following spring, boreholes were drilled to the bottom of each backfilled trench, long hardwood willow cuttings were deeply planted, and the holes were backfilled with sand/compost.
Acreage	0.8 acre
Evapotranspiration Rates	Water use rates for 2001 averaged 7.8 gallons per day per tree for willows and 8.4 gallons per day per poplar.
Climate	Temperature range: -26 to 102F; Elevation: 174 feet; Mean annual precipitation: 44.1"; Growing season: 5/12 -9/23.
Operation/Maintenance Requirements	Mowing, fertilization, replanting, monitoring insect/animal damage.
Final Contaminant Concentrations	
Other Performance Data	Phytoremediation appeared to reduce the volume of groundwater needing e situ treatment by approximately 40%. It is estimated that approximately 340 kg of VOCs were removed in one growing season.

Site Name	Solvent Recovery Service New England (SRSNE) Superfund Site
Site Location	Southington, CT
Cost	Design - $15,500 Greenhouse studies - $40,400 Installation - $115,300 Replanting - $40,700 Maintenance and monitoring - $70,000 TOTAL = $281,900 Net savings of $470,000 expected by 2010
Funding Source	
Lessons Learned	Trees need to be planted earlier in the spring to reduce transplanting shock.
Comments	Manual labor for installation was intense. Only 60% of the original poplar sapling survived, likely due to the late planting and rapid onset of hot weather. Due to a canker infestation, all of the poplar trees were removed in May 2002.
Primary Contact	Karen Lumino, USEPA, (617) 918-1348, lumino.karen@epa.gov
Sources of Information	Phytoremediation at the Solvent Recovery Service New England (SRSNE) site in Connecticut http://www.cluin.org/products/phyto/search/phyto_details.cfm?ProjectID=32 U.S. EPA (2006) *Technology News and Trends* , May 2006. http://www.cluin.org/products/newsltrs/tnandt/view.cfm?issue=0506.cfm#3

Site Name	Sugar Creek Refinery Norledge
Site Location	MO
Project Scale	Full scale
Project Status	Ongoing
Project Start Date	2004
Project Completion Date	
Media Treated	Groundwater
Site History and Background	Former refinery
Site Characterizations	
Contaminants	BTEX
Initial Contaminant Concentrations	
Phytotechnology Mechanisms	Phytodegradation, Rhizodegradation, Hydraulic control, Phytovolatilization
Vegetation Type	Poplars and various other trees
Planting Descriptions	
Acreage	<1 acre
Evapotranspiration Rates	
Climate	Temperature range: -19 to 110F; Elevation: 742 feet; Mean annual precipitation: 36.1"; Growing season: 4/30-10-9.
Operation/Maintenance Requirements	Plant health assessments, fertilization, irrigation
Final Contaminant Concentrations	
Other Performance Data	
Cost	
Funding Source	BP
Lessons Learned	
Comments	
Primary Contact	David Tsao, BP Group Environmental Management Company, (630) 836-7169, tsaodl@bp.com
Sources of Information	Email from David Tsao, 17 July 2006.

Site Name	Sugar Creek Refinery T156
Site Location	MO
Project Scale	Full scale
Project Status	Ongoing
Project Start Date	2002
Project Completion Date	
Media Treated	Groundwater
Site History and Background	Former refinery
Site Characterizations	
Contaminants	BTEX, MTBE
Initial Contaminant Concentrations	
Phytotechnology Mechanisms	Phytodegradation, Rhizodegradation, Hydraulic control, Phytovolatilization
Vegetation Type	Poplars, Willows
Planting Descriptions	
Acreage	<1 acre
Evapotranspiration Rates	
Climate	Temperature range: -19 to 110F; Elevation: 742 feet; Mean annual precipitation: 36.1"; Growing season: 4/30-10-9.
Operation/Maintenance Requirements	Plant health assessments, fertilization, irrigation
Final Contaminant Concentrations	
Other Performance Data	
Cost	
Funding Source	BP
Lessons Learned	
Comments	Some sap flow data available
Primary Contact	David Tsao, BP Group Environmental Management Company, (630) 836-7169, tsaodl@bp.com
Sources of Information	Email from David Tsao, 17 July 2006.

Phytoremediation of Petroleum Hydrocarbons

Site Name	Texas City Chemicals A-Plant
Site Location	TX
Project Scale	Full scale
Project Status	Ongoing
Project Start Date	2002
Project Completion Date	
Media Treated	Groundwater
Site History and Background	Facility is no longer operational.
Site Characterizations	
Contaminants	Naphthalene
Initial Contaminant Concentrations	
Phytotechnology Mechanisms	Hydraulic control, Rhizodegradation
Vegetation Type	Eucalyptus
Planting Descriptions	
Acreage	1 to 2 acres
Evapotranspiration Rates	
Climate	Temperature range: 7 to 107F; Elevation: 102 feet; Mean annual precipitation: 47"; Growing season: 3/17-11/14.
Operation/Maintenance Requirements	Plant health assessments, fertilization, irrigation
Final Contaminant Concentrations	
Other Performance Data	
Cost	
Funding Source	BP
Lessons Learned	
Comments	Divested. Sap flow data available
Primary Contact	David Tsao, BP Group Environmental Management Company, (630) 836-7169, tsaodl@bp.com
Sources of Information	Email from David Tsao, 17 July 2006.

Phytoremediation of Petroleum Hydrocarbons

Site Name	Texas City Refinery LTF
Site Location	TX
Project Scale	Full scale
Project Status	Ongoing
Project Start Date	1998
Project Completion Date	
Media Treated	Soil
Site History and Background	Active petroleum refinery
Site Characterizations	
Contaminants	Oil and gas, naphthalene
Initial Contaminant Concentrations	
Phytotechnology Mechanisms	Rhizodegradation
Vegetation Type	Eucalypts, Switchgrass
Planting Descriptions	
Acreage	26 acres
Evapotranspiration Rates	
Climate	Temperature range: 7 to 107F; Elevation: 102 feet; Mean annual precipitation: 47"; Growing season: 3/17-11/14.
Operation/Maintenance Requirements	Plant health assessments, fertilization, irrigation
Final Contaminant Concentrations	
Other Performance Data	
Cost	
Funding Source	BP
Lessons Learned	
Comments	
Primary Contact	David Tsao, BP Group Environmental Management Company, (630) 836-7169, tsaodl@bp.com
Sources of Information	Email from David Tsao, 17 July 2006.

Site Name	Tibbetts Road Superfund Site
Site Location	Barrington, New Hampshire
Project Scale	Full
Project Status	Ongoing
Project Start Date	1998
Project Completion Date	
Media Treated	Soil, Groundwater
Site History and Background	
Site Characterizations	
Contaminants	Arsenic, Benzene, Toluene, TCE, PCBs
Initial Contaminant Concentrations	
Phytotechnology Mechanisms	Hydraulic Control, Phytodegradation
Vegetation Type	Hybrid Poplar, Understory Grasses
Planting Descriptions	1,400 one year old rooted plants
Acreage	Two acres
Evapotranspiration Rates	
Climate	Temperature range: -33 to 102 F; Elevation: 338 feet; Mean annual precipitation: 36.4"; Growing season: 6/9-9/8.
Operation/Maintenance Requirements	Mowing and weeding
Final Contaminant Concentrations	
Other Performance Data	Trees have grown well and now stand over 15 feet tall. Tree survival in 1998 was 99%.
Cost	$40,000 for Ecolotree portion of project. Entire remedy (including source removal, demolition, water supply extension, controls and monitoring) estimated at $8 Million
Funding Source	
Lessons Learned	
Comments	
Primary Contact	Darryl Luce, USEPA, (617) 918-1336, luce.darryl@epa.gov
Sources of Information	Phytoremediation at Tibbetts Road in New Hampshire http://www.cluin.org/products/phyto/search/phyto_details.cfm?ProjectID=33

Site Name	Toluene-and TCE-contaminated site
Site Location	St. Augustine, FL
Project Scale	Pilot/Field Demonstration
Project Status	Complete
Project Start Date	May 2000
Project Completion Date	
Media Treated	Soil
Site History and Background	
Site Characterizations	
Contaminants	Toluene, TCE
Initial Contaminant Concentrations	
Phytotechnology Mechanisms	Phytoremediation, Phytodegradation
Vegetation Type	Eastern Cottonwood, Eucalyptus
Planting Descriptions	Eastern cottonwood (Poplar deltoids, PD) cuttings and Eucalyptus amplifolia (EA) seedlings were planted in six-tree row plots at 10x3 feet spacing within three replications of a randomized complete block design. Within each plot, three trees were randomly planted separately in plastic training tubes of 2 meters, 3 meters, 4 meters length and 6 inches in diameter. A total of 15 PD clones and 14 EA clones (630 total trees) were planted. Tree height, diameter breast height, and survival were measured accordingly. Toluene concentrations in tissue and air samples were periodically determined.
Acreage	
Evapotranspiration Rate	
Climate	Temperature range: 7 to 103F; Elevation: 30 feet; Mean annual precipitation: 51.3"; Growing season: 3/14-11/16.
Operation/Maintenance Requirements	
Final Contaminant Concentrations	
Other Performance Data	After 29 months of study, the training tubes inhibited above ground growth of PD and EA and presumably root growth and access to groundwater. Trees planted in 2 feet, 3 feet, and 4 feet tubes had 10% less survival and were 0.8 meters shorter and from 0.4-0.8 centimeters less in diameter breas height. PD and EA were statistically equally vigorous, but an EA progeny was the most productive genotype. Tree survival was not correlated with toluene concentrations. Toluene was detected in leaf and branch samples of EA but not PD. Toluene detected in air samples could not be traced to transpiration.
Cost	
Funding Source	

Site Name	Toluene-and TCE-contaminated site
Site Location	St. Augustine, FL
Lessons Learned	Small diameter training tubes were ineffective in promoting PD and EA roo growth, PD and EA were equal in vigor, but an EA progeny was the most productive genotype. Fast-growing trees have phytoremediation potential when the appropriate genotypes of a species are selected together with the necessary silvicultural options.
Comments	Effective phytoremediation of heavy metal or chlorinated solvent contaminated sites by fast-growing trees such as "Eucalyptus amplifolia" (EA), "E. grandis" (EG), eastern cottonwood ("Populus deltoides", PD), and "Salix" species is dependent on tree-contaminant interactions and on tree growth as influenced by silvicultural and genetic factors. An independent May 2002 greenhouse study included 5 propagules each of 9 EA progenies, 24 PD clones, 2 poplar clones, 44 willow clones, and 1 bald cypress. The greenhouse study provided preliminary evidence that young EA, poplars, and willows are more tolerant of TCE than bald cypress, based on changes in tree height, stem diameter, leaf number, and vigor over seven weeks. Within willows, a wide range of tolerance was evident that may be exploite by selection.
Primary Contact	D.L. Rockwood, University of Florida, Gainesville, FL United States, E-mail: dlrock@ufl.edu
Sources of Information	Phytoremediation at toluene- and TCE-contaminated site in Florida http://www.cluin.org/products/phyto/search/phyto_details.cfm?ProjectID=1 03 http://www.epareachit.org/

Site Name	Union Carbide Seadrift Plant
Site Location	Seadrift, TX
Project Scale	Field demonstration
Project Status	Complete
Project Start Date	1992
Project Completion Date	1995
Media Treated	Soil
Site History and Background	The demonstration was performed in the olefins production area near the ol foundation of a demolished natural gas compressor building
Site Characterizations	The soil has a high clay content (51-61%) and contains 2% soil organic matter.
Contaminants	PAHs
Initial Contaminant Concentrations	Naphthalene - Mean > 100 mg/kg Other PAHs - < 5 - 10 mg/kg PAH concentrations in the uppermost foot were significantly higher than in deeper soils.
Phytotechnology Mechanisms	
Vegetation Type	Prairie buffalograss and twelve warm season grasses
Planting Descriptions	One plot was an unvegetated control, and one plot was sodded with prairie buffalograss. The last plot tested twelve different warm season grasses.
Acreage	1,300 square feet
Evapotranspiration Rates	
Climate	Temperature range: 7 to 107F; Elevation: 102 feet; Mean annual precipitation: 47"; Growing season: 3/17-11/14.
Operation/Maintenance Requirements	Common agricultural fertilizer was applied once per year at a rate of 1 pound of nitrogren per 1,000 square feet.
Final Contaminant Concentrations	After three years, naphthalene concentrations were significantly lower in vegetated surface soil than in unvegetated surface soil, but no difference was seen between vegetated and unvegetated treatments in subsurface soil. After three years, there were no significant differences in concentrations of other PAHs in surface soil between the unvegetated and vegetated plots, but concentrations of nine high molecular weight PAHs in subsurface soil were significantly lower in the unvegetated plot than in the vegetated plot.
Other Performance Data	In three years, grass roots only developed in the uppermost foot. Analysis o both root and shoot material indicated no evidence of PAH uptake and bioaccumulations into plant tissue.
Cost	
Funding Source	
Lessons Learned	Kleingrass was determined to have the most potential for growth in contaminated soils and PAH removal in the rhizosphere compared to other plant species.
Comments	

Site Name	Union Carbide Seadrift Plant
Site Location	Seadrift, TX
Primary Contact	Xiujin Qiu, The Dow Chemical Company, qiuxj@dow.com
Sources of Information	Qiu, X., T.W. Leland, S.I. Shah, D.L. Sorensen, and E.W. Kendall (1997) Field study: grass remediation for clay soil contaminated with polycyclic aromatic hydrocarbons. In: Phytoremediation of Soil and Water Contaminants. E.L. Kruger, T.A. Anderson, and J.R. Coats, Eds. American Chemical Society, Washington, D.C. pp. 186 - 199. Olson, P.E., K.F. Reardon, and E.A.H. Pilon-Smits (2003) "Ecology of Rhizosphere Bioremediation" In *Phytoremediation Transformation and Control of Contaminants* . S. McCutcheon and J. Schnoor (eds.), John Wiley & Sons, Inc. Hoboken, New Jersey.

Site Name	Unknown toluene-contaminated site
Site Location	Moonachie, NJ
Current/Former Uses of the Site	Research and development facility
Project Scale	Pilot/Field Demonstration
Project Status	Complete
Project Start Date	May 1997
Project Completion Date	1998
Media Treated	Soil, Groundwater
Site History and Background	
Site Characterizations	Soil consists of clay. Groundwater is 2-7 feet below ground surface, with contamination located 2 to 12 feet below ground surface. Hydraulic gradien is -1.77E-3 to 2.71E-6 meter per meter; hydraulic conductivity is 1.98E-7 to 3.21E-6 meter per second.
Contaminants	Toluene
Initial Contaminant Concentrations	100 to 900 mg/L
Phytotechnology Mechanisms	Phytovolatilization, Phytodegradation
Vegetation Type	Hybrid Poplar
Planting Descriptions	Trees were DN 34 Hybrid Poplars. Trees were initially planted in 1997, with six additional trees planted in the spring of 1998. Single rows of deep-rooted poplars were planted along various sections of the property line (a total of 46 trees). Cultural practices were used to obtain trees dependent upon groundwater, rather than surface irrigation.
Acreage	
Evapotranspiration Rate	
Climate	Temperature range: -8 to 105F; Elevation: 7 feet; Mean annual precipitation: 43.9"; Growing season: 4/15-10/26.
Operation/Maintenance Requirements	Mowing, replanting, monitoring: insect/animal damage, wells.
Final Contaminant Concentrations	
Other Performance Data	Approximately 10% mortality due to transplanting and/or phytotoxicity effects were observed. Project will continue to be monitored.
Cost	Cost includes site preparation, planting, and waste disposal (not analytical) $51,005
Funding Source	
Lessons Learned	Trees need to be planted earlier in the spring to reduce transplanting shock.
Comments	
Primary Contact	Ari M. Ferro, Ph.D., Principal Technical Specialist, Phytoremediation, ENSR, (919) 872-6600, aferro@ensr.aecom.com

Site Name	Unknown toluene-contaminated site
Site Location	Moonachie, NJ
Sources of Information	Phytoremediation at an unknown toluene-contaminated site in New Jersey http://www.cluin.org/products/phyto/search/phyto_details.cfm?ProjectID=122 http://www.epareachit.org/

Phytoremediation of Petroleum Hydrocarbons

Site Name	Whiting Refinery 1st/126th St
Site Location	IN
Project Scale	Full scale
Project Status	Ongoing
Project Start Date	1999
Project Completion Date	
Media Treated	Soil
Site History and Background	Active Refinery
Site Characterizations	
Contaminants	Residual TPH
Initial Contaminant Concentrations	
Phytotechnology Mechanisms	Rhizodegradation
Vegetation Type	Trees, Prairie Species (including clump grasses and wildflowers)
Planting Descriptions	
Acreage	1 to 2 acres
Evapotranspiration Rates	
Climate	Temperature range: -27 to 104F; Mean annual precipitation: 35.8"; Elevation: 658 feet; Growing season: 4/25-10/22.
Operation/Maintenance Requirements	Plant health assessments, fertilization, irrigation
Final Contaminant Concentrations	
Other Performance Data	
Cost	
Funding Source	BP
Lessons Learned	
Comments	
Primary Contact	David Tsao, BP Group Environmental Management Company, (630) 836-7169, tsaodl@bp.com
Sources of Information	Email from David Tsao, 17 July 2006.

Phytoremediation of Petroleum Hydrocarbons

Site Name	Whiting Refinery Cal Ave.
Site Location	IN
Project Scale	Full scale
Project Status	Ongoing
Project Start Date	2000
Project Completion Date	
Media Treated	Soil, Groundwater
Site History and Background	Active refinery
Site Characterizations	
Contaminants	Xylenes
Initial Contaminant Concentrations	
Phytotechnology Mechanisms	Rhizodegradation, Phytodegradation
Vegetation Type	Prairie Species (including clump grasses and wildflowers)
Planting Descriptions	
Acreage	<1 acre
Evapotranspiration Rates	
Climate	Temperature range: -27 to 104F; Mean annual precipitation: 35.8"; Elevation: 658 feet; Growing season: 4/25-10/22.
Operation/Maintenance Requirements	Plant health assessments, fertilization, irrigation
Final Contaminant Concentrations	
Other Performance Data	
Cost	
Funding Source	BP
Lessons Learned	
Comments	
Primary Contact	David Tsao, BP Group Environmental Management Company, (630) 836-7169, tsaodl@bp.com
Sources of Information	Email from David Tsao, 17 July 2006.

Site Name	Wood River Refinery T293
Site Location	IL
Project Scale	Full scale
Project Status	Ongoing
Project Start Date	2003
Project Completion Date	
Media Treated	Soil, Perched Groundwater
Site History and Background	Former refinery
Site Characterizations	
Contaminants	BTEX
Initial Contaminant Concentrations	
Phytotechnology Mechanisms	Rhizodegradation, Phytodegradation, Phytovolatilization
Vegetation Type	Prairie Species (including clump grasses and wildflowers)
Planting Descriptions	
Acreage	<1 acre
Evapotranspiration Rates	
Climate	Temperature range: -18 to 107F; Mean annual precipitation: 37.5"; Elevation: 564 feet; Growing season: 4/30-10/8.
Operation/Maintenance Requirements	Plant health assessments, fertilization, irrigation
Final Contaminant Concentrations	
Other Performance Data	
Cost	
Funding Source	BP
Lessons Learned	
Comments	
Primary Contact	David Tsao, BP Group Environmental Management Company, (630) 836-7169, tsaodl@bp.com
Sources of Information	Email from David Tsao, 17 July 2006.

Phytoremediation of Petroleum Hydrocarbons

Site Name	Wood treatment facility
Site Location	Central Louisiana
Project Scale	Pilot/Field Demonstration
Project Status	November 1999
Project Start Date	
Project Completion Date	
Media Treated	Soil, Groundwater
Site History and Background	Site used for wood preserving.
Site Characterizations	Groundwater contaminated with arsenic, chromium, and PAHs up to 40 ft bgsurface; chromium, copper and arsenic, and creosote mostly in 0 to 4 ft bgs range.
Contaminants	Arsenic, Chromium, Creosote (coal tar), PAHs, Chloroacetic acid
Intiial Contaminant Concentrations	Arsenic - 1900 mg/kg Chromium - 2300 mg/kg PAHs - 930 mg/kg
Phytotechnology Mechanisms	Phytoremediation, Phytodegradation
Vegetation Type	Loblolly Pine
Planting Descriptions	All native vegetation removed and non-natives hand-planted at a density of 500 per acre.
Acreage	30 acres
Evapotranspiration Rates	
Climate	Temperature range: 5 to 104F; Mean annual precipitation: 53.1"; Elevation: 77 feet; Growing season: 3/26-10/31.
Operation/Maintenance Requirements	
Final Contaminant Concentrations	
Other Performance Data	
Cost	
Funding Source	
Lessons Learned	
Comments	
Primary Contact	Timothy Goist, Premier Environmental Services, Inc., (770) 973-2100, togoist@premiercorp-usa.com
Sources of Information	Phytoremediation at a wood treatment facility in central Louisiana http://www.cluin.org/products/phyto/search/phyto_details.cfm?ProjectID=59