

Linking Phytoremediated Pollutant Removal to Biomass Economic  
Opportunities

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## **Abstract**

Phytoremediation (phyto) strategies employ trees, shrubs, and/or grasses for treating contaminated air, soil, or water. These strategies include buffers, vegetation filters, *in situ* phytoremediation plantings, and percolation controlling vegetative caps.

The design parameter that separates phytoremediation from landscaping is purposefully placing and growing a root-zone reactor volume with predictable pollutant removal performance. This phyto reactor integrates with other engineered systems to cover landfills, treat petrochemical spills in soils, intercept a soluble subsurface plume, and capture non-point surface sediment entrained in urban or field runoff.

There are many potential economic opportunities for biomass associated with phytoremediation, including bioenergy and traditional industrial products such as solid wood products and reconstituted products (i.e. paper, chip board, laminated beams, extruded trim).

More intangibly, phyto creates environmental benefits such as soil erosion control, carbon sequestration, and wildlife habitat. Phyto also creates socio-economic benefits by diversify regional manufacturing into new products that employs local labor, thus building value-added industry. Alternative crops develop a greater diversity of products from the farmland, making the regional economy less exposed to global commodity crop price fluctuations.

Thus, a strategic phyto treatment of non-point agricultural runoff would help diversify land use from annually tilled crops (corn, soybeans, wheat) into perennial, untilled tree crops. A landscape rebuilt using phyto would create diversity represented in business potential, healthier air and water, wildlife habitat, and aesthetics.

Moreover, phyto provides local and current pollutant treatment. Such timely treatment of pollutants that would otherwise move to our downstream or downwind neighbors is key to the environmental justice concept.

We present four case study summaries to illustrate installed commercial applications of phytoremediation.

*Keywords:* phytoremediation, poplar, willow, streamside buffers, wastewater, vegetation filter, vegetative cap, environmental justice, landfill, lagoon, brownfields

## **1. Introduction**

Short rotation woody crops have been grown from the tropics to tundra throughout the world for centuries. The principal species planted on short rotations are *Eucalyptus*, *Pinus*, *Populus*, and *Salix* [1]. The primary use of the woody biomass has been industrial wood (fiber for paper, structural wood for construction), although in many developing countries it is used as stored energy for fuel wood [2]. The residuals from industrial wood products (e.g. bark, lignin, side branches, roots) have long been used by industry as process bioenergy.

Willows have been planted in Sweden since the 1960's specifically for bioenergy heat by burning in district heating plants [3]. In Brazil, short rotation *Eucalyptus* is used for industrial charcoal production, paper pulp, construction wood, and local bioenergy electric power. Poplars and willows have also been used for riparian plantings for centuries [4].

There are new economic opportunities for biomass from short rotation trees planted for pollutant removal with phytoremediation strategies. The term 'phytoremediation' (hereafter, phyto) describes a process where an air, soil, and/or water contaminants are captured and 'remediated' by trees and other plants. The

primary difference between short rotation woody crops and phytoremediation systems is the value attributed to the specific pollutant removal function.

Pioneering phytoremediation applications with willow and poplar drew heavily on growth and yield data from early bioenergy research. In 1987, these data provided ‘strong inference’ to predict water, nitrogen, and phosphorus removal potential of poplars [5].

Pioneering projects with various phyto applications have demonstrated acceptable performance, but also limitations [6]. Now, next-generation phyto systems are designed to improve operational control, incorporating computer-controlled monitoring, using genetically improved plant materials and arboricultural husbandry. Rules that specify environmental remediation outcomes are being modified by state and federal regulatory agencies to allow appropriate phyto systems that will compliment and/or replace more conventional engineered pollutant removal systems.

Linking phytoremediated pollutant removal with biomass production offers attractive economic alternatives that cycles pollutants from water and air into value-added products that create jobs.

In this paper we present:

- 1) Emerging phytoremediation technologies, including buffers, vegetation filters, *in situ* phytoremediation plantings, and percolation controlling vegetative caps,
- 2) Four case study summaries for installed phytoremediation systems
- 3) Potential economic opportunities for biomass produced by phytoremediation

## 1.1 Terminology

The terminology used here for phytoremediation mechanisms are unique and defined by the US Environmental Protection Agency [7] and the US Department of Agriculture [8]:

- *phytoremediation* (*phyto* - Greek for plant) a general term for several ways plants clean up, or remediate sites by removing contaminants from the soil and water [8]. The terms *phytoextraction*, *rhizofiltration*, *phytostabilization*, *phytodegradation*, *rhizodegradation*, and *phytovolatilization* are used as in US Environmental Protection Agency [8].
- *brownfields*, industrial areas that have contaminated soils and groundwater from past chemical leaks, but have value for economic development if the pollutant is controlled and removed.
- *buffers*, strategically placed plants planted for non-point pollutant interception and treatment where surface water, groundwater, and wind pass through by plant sorption, surface runoff interception, and root zone activity [8].

## 1.2 Phytoremediation treats air, water, and soil pollution

New phyto technologies for remediating streamsides, brownfields, landfills, and other contaminated sites using tree planting are emerging worldwide [6], [9], [10]. Most phytoremediation applications use human-installed streamside riparian buffer strips or vegetation filters. A riparian buffer or corridor consists of a strip of planted trees, shrubs and/or grasses along a wetland, stream, river or lake. Streamside buffers are planted between a contaminant source, like a plowed agricultural field, and the drainage. A riparian buffer is the strategic filter that

slows and decreases the runoff flow, depositing sediments, fertilizers, plant debris, and humic carbon otherwise deposited in the stream flow [11], [12].

Vegetation filters are designed to manage specific sources of nutrients, municipal wastes, landfill leachate, and biofuel ash [13]. These phyto plantings are not necessarily related to a lake, river or wetland.

Vegetative caps incorporate plants, soil, and associated microbes as cover alternative to clay or plastic caps installed to decommission landfill and lagoons. The plants control erosion, take up rainwater, decrease runoff into nearby areas, and improve groundwater quality. At some metal and/or metalloid mining or disposal sites, plants used for phytoremediation absorb enough contaminants that leaves and stem are classified as “toxic”; and may require post-harvest disposal of as hazardous waste. In the case of metals clean up, the metals can sometimes be reclaimed from the plants and re-used [10].

## **2. Phytoremediation processes and strategies**

### **2.1 Water consumption**

The key to phytoremediation success is predictable plant water uptake. Plants take up essentially all nutrients as water-soluble compounds through the roots or foliage. Some insoluble compounds are also taken up by plants through water uptake [6]. Thus, for uptake to occur, contaminants must reach the plant through water in the root zone.

Crop plants grown in the irrigated lands pump predictable quantities of water based on models [14]. Many crop plants use water in ratio of 270-450 kg water per kg (600 – 1000 lb water per pound) of net biomass production. Tree water transpiration is directly related to biomass growth and the tree’s water use efficiency. Because the tree has more surface area placed above the soil surface,

more water is evaporated and transpired than grass surface. At full canopy, the potential evapotranspiration (PET) of poplar is predicted to be 130% compared to grass.

Poplar growth and inferred water consumption can be accurately estimated as a function of the tree size (i.e. diameter, height, and leaf area). Poplars are known to take up between 20 and 50 kg (44 to 110 pounds) of water per tree per day (14). In the Midwestern U.S., the predicted PET for poplar is 21.6 cm (8.5 inches) for June. This uptake amounts to an average of 69,600 liters/hectare/day (7,600 gallon/acre/day) water removal. Assuming a dense planting of 720 trees/acre, this uptake is an average tree removal rate of 39.5 l/tree/day (10.6 gal/tree/day). Data collected from around the United States specifically from phyto projects around the use document water removal performance by poplar within this range [15].

In most phyto applications, roots dewater soil pores, creating storage capacity that again refills with water. This captured root-zone water becomes groundwater and decreases the storm water surge flow. Phyto approaches thereby capture surface water contaminate and reduce peak storm water peak flow in streams.

## 2.2 Rhizosphere microbes

In the rhizosphere around the roots soil microorganisms and fauna exist that can decompose organic substances for nutrition and carbon [6]. Plant roots also provide essential nutrients and organic carbon for microorganism growth. These rhizosphere processes often catalyze petrochemical contaminant breakdown in the soil (Fig. 1).

## 2.3 Matching the plant to the contaminant and site

The complexity of plant growth is compounded in phytoremediation because human activity has changed native soils, stripped native vegetation, and added human-created chemicals. An important principle of phytoremediation is to match the proper plant species and clone to the contaminated site. Consideration must be given to soil, microclimate, region, pests and diseases as well as the contaminant to be cleaned up.

Plants vary in genetic and cultural response when exposed to the wide range of regulated situations. Some plants are better for taking up heavy metals, others for volatile organics. A consideration of growing concern in selecting the appropriate plant for the phytoremediation application is whether it is native to the ecosystem where the phytoremediation is taking place. This choice is particularly important for sites near natural areas that need to be protected. Non-native species (and some natives, too) could escape from the phytoremediation site, take root nearby, and potentially threaten important native species [10].

One approach to matching the proper plant material to the site for phytoremediation is with a “phased phytoremediation strategy”:

Phase 1: conduct experimental screening studies of plant materials under controlled conditions at the site using local, native plant materials, contaminated soil, and water to evaluate growth, mortality, and contaminant uptake.

Phase 2: verification, narrow the choice of Phase I plant materials for the specific site in a second year to refine first year results.

Phase 3: demonstration plantings and testing on a small scale in the ground at the site, and

Phase 4: scale up and deploy the plant material with proven merit for remediating the specific contaminants in the design chosen for the site. This conservative strategy allows assurance that the native plants are capable of the

clean up required. It also fits within the policy and administrative time frames for clean up of brownfields and landfills [10].

## 2.4 Poplar and willow phyto performance

Poplars (*Populus spp.*) and willows (*Salix spp.*) are the most common tree species used for phytoremediation because they grow rapidly, have many and deep roots, and take up large quantities of water [16]. Poplars and willows grow large root systems with a high proportion of fine roots that are less than 1mm in diameter. These roots not only take up substantial quantities of water and nutrients, but they also provide the surface area for fungi that form beneficial mycorrhizae. Poplars and willows take up a wide variety of pollutants including fertilizers (nitrate, ammonia, phosphorous), inorganic metals and metalloids, petrochemical compounds (fuels, solvents, pesticides, intermediates), and soluble radio nuclides [10].

## 3. Phytoremediation applications and case histories

### 3.1 Streamside buffers

#### 3.1.1 General description

Surface waters are contaminated by two primary sources – pipe-delivered wastewater from urban / industrial sources and non-point runoff water draining agriculture and urban land. Non-point pollutants from the agricultural Mississippi River drainage in the U.S. drinking water safety regulations and damage ecosystem health throughout the watershed and into the Gulf of Mexico.

A tree buffer has two characteristics – it hugs a streams bank and is thin in the width dimension compared to the stream length protected. Riparian buffers are planted in a corridor along watercourses as the final filter for runoff draining the

land into the streams. Many poplars and willows are naturally adapted to riparian areas and saturated conditions [14]. They survive in low-oxygen root zones. They have the genetics to take sparse nutrients from poorly consolidated soils, such as sand bars. The species thrived on the land before western European settlement, and were used by pioneers as painted barn siding.

Though not the only option, poplar and willow are naturally well suited to quickly colonize and revegetate the riparian corridors that have been tilled for annual crops. Poplars and willows are the primary tree species of choice for phytoremediation buffers in North America, Europe, and New Zealand [11], [17], [18].

Beginning in 1988, the Leopold Center for Sustainable Agriculture, located at Iowa State University, Ames, Iowa, USA, supported early research focused on pollutant removal from tilled crop runoff using tree buffers [11], [12]. The early data from buffers demonstrated a 98% reduction in subsurface seeping nitrate-nitrogen [5], [19]. Expanded to a full-scale watershed, sediment was substantially decreased by more than 80% two years after establishment [20].

Iowa State University, Ames, Iowa, USA has operated a multi-disciplined research program that documented 12 years of changes induced by mixed species buffers in stream corridors [11], [12]. Researchers worked with farmers to develop a regional watershed corridor planted with zones of trees, shrubs, and warm-season grasses. The results from their research are summarized:

- Water pollutant reduction – sediment mass was reduced 90%; nitrogen and phosphorus masses were reduced 80%.
- Groundwater pollutant reduction - nitrate was reduced 90% from the groundwater seeping through the root zone from field to stream.
- Stream bank stabilization – cut stream bank erosion was reduced by more than 80% compared to row-crop and grazed fields.

- Startup efficiency – maximum sediment removal occurred within five years. The maximum nutrient removal occurred in 10-12 years.
- Buffer soil organic matter content – organic carbon increased by up to 66% in the riparian soil upper root zone.
- Wildlife benefits – five times as many bird species were enticed and supported compared to row-cropped or heavily grazed fields.

The US Department of Agriculture (USDA) funds the Conservation Reserve Program (CRP) CRP pays farmers the equivalent of annual rent for 10-year or 15-year contracts to convert annually tilled, erodible ground into a perennial prairie or forest. It shares in planning, planting, and maintenance costs for these riparian and prairie plantings [21]. The CRP riparian buffer forest management plan [21] follows prescribed rules for landscape position, width, species mix, and pest control.

In the CRP tree cycle, farmers develop experience growing fast-growing trees. Within the 10 or 15-year contract term, healthy and well-formed trees will create and store value to be harvested at the end of the contract term. In some regions, market for wood fiber already exists, but there is time to create market for the buffer-grown wood crop. If all desired benefits from a tree buffer are accounted and rewarded, a long-term program could emerge that will be more dependent on market and less on subsidy. (Fig.2).

### 3.1.2 Riparian buffer case history

In Spring 2002 near Lowden, Iowa, USA, a landowner and tenant farmer converted a corn cropped corridor on both sides of a stream into a riparian tree and grass buffer. It was funded and authorized with approval from three agencies – USDA Farm Service Agency, Iowa Department of Natural Resources, and USDA

Natural Resources Conservation Service [21]. The buffer management plan details wildlife habitat development, erosion control, and harvest as specific outcomes from this buffer.

The total tree-planted area is 6.3 hectares (15 acres). The total buffered stream length is 1500 m. (4950 ft). Following the Iowa State Buffer model, each buffer side is 20.1 m (66 ft) wide, contains six rows of trees and a mixed grass species understory. The trees include two clones of *Populus spp.* Trees were planted at the rate of 1350 trees/ha (550 trees/acre), with the spacing between trees averaging 2.2 m (7.1 ft) within-row, and 3.3 m (10 feet) between rows.

A planned poplar harvest will follow CRP contract completion. This approach will allow farmers to have the maximum flexibility for land management. Wood production for value-added products is essential to keep the landowner more stable than the existing row-crop tillage system. Harvest options include:

- the trees can all be allowed to continue growing,
- the poplar can be harvested and longer-lived hardwoods can be left, or
- the land could be converted back to row-crop production following root removal – though that decision would signal a failure in the economic system reflecting product and ecosystem values.

With good husbandry including weed control and some pruning, the trees in year ten will average 35 cm (14 inch) diameter at breast height. Assuming 500 trees survive per acre and a dry wood yield of 91 kg/tree (200 lb/tree), the harvested mass will be approximately 106 mt/ha (50 t/acre). This wood will be available for wood, fuel, or chips for local products.

## 3.2 Vegetation filters for wastewater treatment

### 3.2.1 General description

Vegetation filters are designed to intercept pollutants in subsurface plumes or surface runoff from municipal wastes such as wastewaters, sludges, landfill leachate, and/or biofuel ashes [13]. Plantings of trees, shrubs or grasses take up the contaminants that would otherwise pollute the environment. When trees are periodically harvested, the wood will contain water-soluble compound in the root zone. Some of the restricted pollutant, such as nitrate nitrogen, ammonia nitrogen, trichloroethene, zinc, are taken into the plant and removed from the site soil. Most pollutants never enter the plant but are sorbed or reacted in the root zone reactor by soil microbes. Some organics are now shown to metabolize in the root and plant cells. When metals are involved, there can be mobilization through the plant for use in metabolism or accumulated in the leaves. Thus, phyto is not safe if the contaminant is a radionuclide, which can blow with a fallen leaf from the site.

When the irrigated water does not contain harmful compounds, the nutrients and water removed from the site result in biomass production. Healthy plants maximize root activity, water uptake, and pollutant containment. Often the phytoremediation strategy with vegetation filters is to pump contaminated water from lagoons or groundwater wells, thereby irrigating trees and/or forbs.

### 3.2.2 Riverbend Landfill buffer case history

A vegetation filter to treat landfill leachate was designed in 1992 for Riverbend Landfill, McMinnville, Oregon USA. A poplar phyto system was designed to grow a root system with sufficient capacity to adsorb and mineralize organic and nutrient compounds (Fig.3). The system was in lieu of leachate treatment at the McMinnville Municipal Wastewater Treatment Plant, or building a private biological treatment plant for surface discharge to the adjacent Yamhill River.

Since 1993, leachate drains from the landfill bottom collection system into a lined 26,000,000 liter (7,000,000 gallon) storage lagoon. In 1992 and 1993, 35,000 trees were planted on 6.9 ha (17 acre) field adjacent to the lagoon. The irrigated footprint was 5.9 ha (14.5 acres).

In a normal annual operation schedule, this stored leachate accumulated between November – April and then metered through spray irrigation onto the growing trees between May and October. Irrigated leachate percolates into the poplar tree root zone. The site was monitored by measuring soil moisture content and sampling three wells placed 2.5m (8 ft) deep. The soil moisture content was monitored to adjust and match the leachate application rate to plant transpiration. Though leachate contains many soluble and particulate compounds, ammonia nitrogen was the principal regulated contaminant controlling application rates.

#### 3.2.2.1 Irrigated leachate results

During the ten years of leachate application, the performance statistics were tabulated in annual reports. These results give perspective to the pollutant treatment capacity developed in the root zone:

- In ten operating seasons the total amount of leachate treated on site: 267 MM liters/site (70.6 MM gallons/site) or 45.1 MM liters/ha (4.87 MM gallon/acre).
- Average leachate water treated per year: 27 MM liters/site/year (7.1MM gallons/site/year, or 4.6 MM liters/ha/yr (487,000 gallons/acre/year).
- Annual irrigation rate using terms common in agriculture is 115.4 cm/ha/yr (18.4 inches/acre/year).

#### 3.2.2.2 Nitrogen treatment results

Nitrogen treatment results were based on monthly leachate analyses.

- Ten-year total ammonia and organic nitrogen treated on site: 19,800 kg N (43,600 lb N) or 3,346 kg N/ha (3,007 lb N/acre).
- Average ammonia and organic nitrogen treated per year: 1981 kg N/yr (4,358 lb N/yr) or 338 kg N/ha/yr (301 lb N/acre/year)

### 3.2.2.3 Groundwater monitoring results

Groundwater was sampled at three 2.5 m monitoring wells on a three-month schedule and analyzed for several indicator compounds. Average nitrate-nitrogen ( $\text{NO}_3\text{-N}$ ) concentration did not exceed the drinking water standard (10ppm) during the irrigation season from May through October. In the late autumn the quantity of  $\text{NO}_3\text{-N}$  that leaked from the irrigation field following the first flush of winter rain was similar to a fertilized agricultural field (i.e. 20-30 ppm  $\text{NO}_3\text{-N}$ ).

### 3.2.2.4 Wood growth estimate

The trees grew well when irrigated with leachate that contained all the essential plant nutrients, along with petrochemical organic compounds, and salts below toxicity thresholds (Table 2). Tree growth was estimated for the poplar clone DN-34 using non-destructive diameter measurements. After eleven growing seasons, following measurement of 26 trees, the estimated 'average' aboveground wood biomass is 90 kg/tree (197 lb/tree). The dry matter content is 47.2%.

### 3.2.2.5 Water and nitrogen cycling

The poplar trees grew well after receiving landfill leachate irrigation. The trees at this site are expected to be harvested in 2003. Based on these data for applied water mass, approximately 159 kg of leachate were consumed for each kg of aboveground poplar biomass growth. Approximately 1 kg of nitrogen was applied per 45 kg of aboveground wood growth.

In the view of the owner, the Oregon Department of Environmental Quality, and the engineering consultant, the prototype worked sufficiently well to achieve the permit criteria. The next generation phyto vegetation filter was established on an adjacent 30 ha (75 acres), and leachate irrigation treatment will begin in 2003.

### 3.3 Vegetative Caps

Humans have buried unwanted wastes in natural or man-made holes in the ground throughout recorded history. Since 1976, the U.S. solid waste industry has made significant changes to the design of liners, covers, drainage systems, and biogas control. Now, Federal and state regulations require owners have a program to contain and treat listed pollutants that leak from landfill and cause insults to the air, soil surface, or draining water [22].

Landfill closure regulations are conceptually progressing from waste containment to stabilization via a biocell reactor design [23]. The first prototype phyto cap designed under the new solid waste rules was planted in 1990 at Lakeside Landfill, Beaverton OR. It used poplar trees to pump water from a root zone created with a predictable water storage capacity [24].

As shown schematically in Figure 3 the engineered ‘sponge’ of soil holds and releases water to the roots that ‘pump’ soil moisture. This ‘sponge-and-pump’ mechanism can be modeled using data assuming future climate, soil properties, root zone depth, and biomass growth.

Alternative closure covers that use vegetation planted in a soil layer over land filled waste are being studied for percolation control. Because of financial and ecological interest in alternative landfill covers, an extensive demonstration program is being conducted by the U.S. Environmental Protection Agency [25].

This root zone reactor design is the key design difference between vegetative covers and geosynthetic covers. A vegetative cover creates the following beneficial situations:

- By achieving predictable percolation control, vegetative caps displace the need for relatively expensive geosynthetic caps constructed with plastic sheets or clay layers. The long-term future of a percolation-controlled phyto cap is significantly different than such geosynthetic covers. Geosynthetic caps inhibit natural succession because regulatory rules require removal of all trees and deep-rooted plants to maintain the integrity of the barrier layer. In contrast, vegetative caps can be managed such that water control can immediately improve while mimicking natural succession of a poplar and willow forest into a mixed species forest.
- Sufficient transpiration capacity by the plant system requires healthy, vigorous growth. Thus the phytoremediation function will grow a significant mass of biomass in most moist climates if a vegetative cap is to achieve the control required by regulations for buried solid waste management.
- With a well-conceived forest management plan, there is a possible harvest, wildlife diversity, and recreational opportunities when indicator data demonstrate low risks to visitors.
- The rooted soil cover supports a methanotrophic microbe population capable of mineralizing methane gas and water-soluble chemicals that pass through the cover, or that the roots penetrate.

### 3.3.1 Duvall Custodial Landfill - case history

#### 3.3.1.1 Overview

The -King County Department of Public Health, located in Seattle Washington, USA approved the design of a phyto system on an evaluation basis in lieu of a geomembrane raincoat cover. High-value housing and intact conifer forest remnants surround this landfill. This pre-Subtitle D landfill had a 1 - 2 meter thick soil cover vegetated with grass. Numerical water balance modeling predicted that a poplar tree cover could dehydrate the soil during the growing season, thus creating water-holding capacity to reduce winter rainfall percolation.

King County Solid Waste staff, Aspect Engineering (Bremerton WA.), and Ecolotree<sup>®</sup>, Inc. (North Liberty IA.) designed and installed a 5 ha vegetative cap in April 2000. The total project cost, including design, instrumentation, irrigation system installation, 10,000 poplar trees installed, and first year operations was \$407,000 (USD). Moreover, no soil placement was required. Cost savings were estimated at 60% compared to available geosynthetic cover designs.

#### 3.3.1.2 Vegetative cap results

1. Tree survival was 98% in the first year, and 97% after three growing seasons (Fig.4).
2. Tree height at three years ranged from 4 to 8 m (13 to 26 feet).
3. Composted municipal biosolids applied as mulch protected roots from western mountain vole damage and greatly increased tree growth. Based upon three growing seasons, compost applied in 2000 on a small plot improved growth by 1000% in contrast to adjacent plots containing the same tree variety but fertilized with mineral nitrogen and phosphorus. Phosphorus was the critical macronutrient from the compost, but micronutrients also were available.

4. Compaction is based on the cover soil texture, how it was placed, and climate. Compaction appears to be the most important variable that is difficult to modify when installing trees. With time, compaction affects wood growth patterns. Soil density at the site was measured using a neutron probe densiometer 30 months following tree installation. In zones with the fastest growth, soil density is 1,444 kg/ m<sup>3</sup> (90 lb/ft<sup>3</sup>). In a closed landfill area nearby with 2,007 kg/ m<sup>3</sup> (125 lb/ft<sup>3</sup>) compacted clay zones, tree growth for same clones of trees grew only 25% as much as the fastest growing trees.
5. Water uptake patterns show climate, root depth, and growth influencing available water mass in root zone.
6. Wildlife ecology continues to attract a mixed species of forest edge predators, birds, and raptors. The potential exists for this landfill cover to become a park or wildlife preserve in the future after all concerns of safety are addressed.

### 3.4 *In situ* phytoremediation plantings

*In situ* phytoremediation plantings use trees, shrubs, or grasses installed for subsurface treatment of inorganic and organic chemical spills caused by man. These sites are often called polluted “brownfields” and result from industrial development and petrochemical spills. Such sites are a globally issue because of the international petrochemical economy.

With an *in situ* phyto approach, plants are deployed where the contaminant exists at concentrations that allow growth. For any engineered approach to brownfeild cleanups, criteria normally used to compare and select alternative cleanup methods include:

- n Protection of human health and the environment
- n Attainment of cleanup standards

- n Source control
- n Long-term reliability and effectiveness
- n Reduction of toxicity, mobility, or volume of contaminants
- n Short-term effectiveness
- n Implement ability
- n Cost

The desired outcome is removing, degrading, or containing health-threatening compounds. Soil cleanup *in situ* is normally a slow process, compared to removal and transfer to a regulated landfill, but has advantages. The phyto strategy has the potential to provide aesthetics from natural systems while being effective and economical [26]. Phytoremediation of polluted brownfields is a relatively new technology that has the benefit of creating a forested environment that provides all the benefits attributed to trees.

### 3.4.1 Ashland Chemical Petrochemical Depot – case history

#### 3.4.1.1 Site overview

The Ashland Chemical, Inc. facility in Milwaukee, Wisconsin, USA is typical of many petrochemical processing, shipping, or application businesses around the world. Due to no criminal negligence and following standard operating procedures of the day, historic accidental fuel and solvent spills resulted in soil and groundwater contamination around storage tanks.

The site is adjacent to the Menomonee River, with industrial fill placed over soil and bedrock at 3 to 6 m (10–20 ft) subsurface. Typical in such sites, the soil contained a blend of petroleum-related organics, polyaromatic hydrocarbons, and chlorinated organics such as tetrachloroethylene (PCE) and tetrachloroethane (TCE).

Ashland Chemical (Columbus OH), RMT Inc. (Milwaukee WI), and Ecolotree, Inc. (North Liberty IA) together designed and installed a phyto system to increase petrochemical degradation and slow movement to the river. The concept was to install tall poplar trees into 3 meter-deep boreholes that tapped the near-surface groundwater adjacent to the river. Phyto processes would be both a vegetation filter and a vegetative cap. Wisconsin Department of Natural Resources staff as the remedial solution approved phytoremediation. They had considered over 20 other alternative cleanup options including remove all soil, run a vapor extraction system, and incinerate organics. The phyto system was allowed to be planted with provision for extensive monitoring, including: continual depth-to-groundwater measurements, groundwater and soil testing for residual organics, data-logged soil moisture sensors, subsurface root observation tubes, and leaf nutrient analyses. The information regarding installation and measured performance was compiled in an extensive document [27].

The design included 485 rooted poplar trees, each 3-4.6 m (10-15 ft) tall planted in May 2000. Trees 4.6 m (15 ft) were planted in holes excavated 3 m (10 ft) below ground surface in the three rows closest to the river. The remainder of the site under most of the tank pads was planted with 3 m (10 ft) trees in 1.7 m (5 ft) deep augured holes. To improve growing conditions for tree roots and create faster root zone reactions, air was pumped through an aeration system to 3 m (10 ft) subsurface.

#### 3.4.1.2 Results to date

The trees have grown well by following a specific maintenance program. The resulting growth was as follows:

- Tree survival was 88% initially, and 99% after replanting phytotoxic areas.

- Trees have tripled in height, some growing 7.3 m (24 ft) in three growing seasons.
- Root growth is extensive, with new roots observed 3 m (10 ft) subsurface and 1.2 m (4 ft) radius from the tree stem.
- Subsurface aeration has increased sub-surface oxygen content from 5% to 15–18 %.
- Groundwater depth fluctuations have been measured on a daily cycle during the growing season.
- Contaminant removal was greatly accelerated by the installed phyto system. Petroleum volatile organic compounds (VOC) have been measured with a 200% increase in the degradation rate. Chlorinated VOC's have been measured with a degradation rate increased by 1000%.
- The site is aesthetically attractive from the stream and the adjacent residential community.
- At this time, this site has the interest of the regulatory community, and is creating a regulatory acceptance of the phyto option for cleaning up other chemical spills.

#### **4. Biomass economic opportunities from phyto-mediated pollutant removal systems**

There are many tangible and intangible economic opportunities for biomass production from phyto-mediated pollutant removal systems. Some are from more traditional uses, although there are many new non-traditional uses under development using small diameter trees [28]. Primary and secondary products from poplar and willow wood include bioenergy, pulp and paper, lumber, veneer and plywood, composite panels, structural composite lumber, pallets, furniture, containers, chopsticks, and animal feed [2]

Intangible benefits include carbon sequestration, soil erosion control, protection plantings, urban plantings environmental regulation and justice, and aesthetics (i.e. greening).

#### 4.1 Bioenergy

Poplars and willows from phytoremediation systems are environmental acceptable sources of biomass for bioenergy as well as wood products. Wood chips and/or pellets can be mixed (co-fired) with coal to produce electricity. This approach is cleaner, cheaper, and more environmentally acceptable than coal alone [29]. Pilot tests of co-firing of woody biomass have been successfully conducted, although at a small scale. Moreover, new biomass burning power plants are under construction in the USA. For years the pulp and paper industry has also used wood residues from short rotation tree plantations for power generation within their own mill facilities. Wood chips and wood pellets made from small diameter trees thinned from forests are also being used. Unfortunately, the scale of this approach in the USA remains small. Biofuels are gaining in popularity in Europe as they are a renewable fuel; they are neutral with respect to carbon dioxide emissions thus, energy plantations help countries decrease their greenhouse gas emissions in accordance with the Kyoto Protocol [30].

Another bioenergy heating application is the small-scale close-coupled gasifier for home and farm use. These systems convert biomass of varying moisture contents to energy with good fuel efficiency, minimal maintenance, and low cost while minimizing environmental pollution problems. Again, while they are readily available on the market, they are not yet used on a large scale. Wood pellets are used for firing small-scale home and farm heating units throughout north temperate regions of the world. Dozens of commercial wood burning stoves are available on the market, and there is widespread local use in areas where wood sources are available.

#### 4.2 Pulp and paper

Poplar wood from natural forests as well as short rotation plantations has been used for years as a source of wood for pulping. The major paper products from poplar pulp include specialty products, such as tissues, building boards, and general-purpose pulps [31]. Short rotation poplar biomass from phytoremediation buffers would help take pressure off the natural forests as a source of wood supply, thus preserving more natural forests for other uses.

#### 4.3 Solid wood products

Poplar wood has been used for solid wood products for decades. It can be used for structural lumber, but is more often used in non-stress graded lumber applications such as pallets, boxes, furniture components, lumber cores, and interior trim [31]. Hall et al [32] and Kretschmann et al [33] have shown that hybrid poplar wood can be used successfully for solid wood lumber products. This wood could be produced rapidly from any of the phytoremediation buffer systems. Again, wood from phytoremediation and buffers would help to take the pressure off natural forest harvests and imports of solid wood.

#### 4.4 Composite wood products

Poplar wood is increasingly used as a source of material for composite wood products [31]. These products include a wide range of wood products including particleboard, fiberboard, wafer board, oriented strand boards, and plywood as well as composite lumber products. These products are used for both interior and exterior use. According to Balatinecz and Kretschmann [31], the composite wood products from poplar wood are likely to increase in the future. Other potential products from poplar and willow wood include extruded signs from wood powder, chopsticks, hockey sticks, and cricket bats.

#### 4.5 Feed products

The foliage from poplars is rich in protein and can provide a source of animal feed in certain regions of the world [34]. This animal feeding use has been common in developing countries for centuries.

#### 4.6 Intangible economic benefits

Until recently society has not put much economic value on environmental benefits from trees such as clean air, soil, and water. However, times are changing in this regard as the world population grows and the public becomes more environmentally conscious. We believe biomass production from phytoremediation and buffers have much economic potential in the future for these environmental benefits.

##### 4.6.1 Carbon sequestration and management

Short rotation woody crops fix carbon dioxide from the atmosphere and store carbon both above and belowground as biomass. Moreover, the harvested portions of the trees displace other products that are made from non-renewable fossil fuels [30]. One of the ways to decrease greenhouse emissions in the future is to plant fast growing woody crops on unproductive land thereby sequestering carbon and displacing fossil fuels by harvesting woody biomass for bioenergy, or by storing carbon in long-lived woody products [30]. Currently, there is a market for “carbon credit” trading by corporations, and there has been some discussion of expanding carbon sequestration credits to small landowners in the future. Short rotation poplar and willow crops deployed as phytoremediation buffer systems would qualify for these carbon credits, and if planted at large scales would contribute greatly to atmospheric carbon dioxide gas reduction [16].

#### 4.6.2 Soil erosion control

Each year billions of tons of topsoil are eroded down major river drainages of the world. In the United States soil erosion in the Mississippi River drainage accounts for some of the largest soil carbon losses in the nation [35]. Moreover, the millions of tons of soil deposited in the Gulf of Mexico carries with it significant quantities of nutrients, herbicides, and pesticides creating a huge “dead zone” of thousands of square kilometers where animal and plant life are minimal. This erosion is largely was caused by centuries of clearing of streamside forests for agriculture. Planting a multi-species buffer of trees, shrubs, and grasses along streams in agricultural areas have been shown to greatly decrease the aforementioned soil erosion [11], [36], [37], [38]. It is difficult to place an economic value on such huge environmental improvements. Currently, society does not place a direct value on such practices, other than providing farmers assistance for establishing and maintaining buffers on their farm [22]. In the future, it should be possible to establish streamside buffers of trees, shrubs, and grasses and harvest an economic biomass crop from these buffers at the end of a short rotation. In this way, society is served and farmers are able to realize a profit for their efforts.

#### 4.6.3 Protection plantings

Protection plantings of trees and shrubs on farms have been used for centuries. They consist of single or multiple rows of trees and /or shrubs established for environmental purposes around farmsteads and agricultural fields. They moderate heat in summer and cold in winter for people and animals, thereby enhancing land value, beauty, noise reduction, and wildlife habitat. Around fields they protect crops by decreasing soil erosion and moisture loss, increase populations of wildlife, serve as site for animal manure removal, and produce biomass for bioenergy and wood [16]. These plantings increase crop yields by decreasing stress on crops. They also can produce salable small diameter wood products from “timberbelts” in a short time frame, while improving wildlife habitat

and other environmental benefits [39]. Again, it is difficult to place a value on these environmental benefits. If the trees could be harvested from protection plantings after a reasonably short rotation, society would gain both the environmental and economic benefits of such efforts.

#### 4.6.4 Urban plantings

Trees in urban settings can greatly improve the environment through their phytoremediation properties. Moreover, these plantings are known to provide societal value by offering a “green” landscape thereby reducing stress on urban inhabitants, decreasing violence, and improving neighborhood community pride [10]. Therefore, urban plantings have significant psychological and social implications that are difficult to measure economically. Some communities are looking into periodic harvests of such urban plantings to gain the positive benefits of both phytoremediation and potential bioenergy production, while at the same time enhancing bird habitat in the urban landscape. In this way, society reaps “win-win” benefits during and after the tree plantation’s lifespan.

#### 4.6.5 Environmental Justice

Environmental regulations often require clean up when contaminants such as fertilizers and herbicides exceed an established threshold (i.e. nitrates, or atrazine in groundwater). Phytoremediation can allow the landowner to remediate the site *in situ* to comply with the law.

Environmental justice is the fair treatment of people of all races, cultures, and income with respect to the development, implementation, and enforcement of environmental laws, regulations, programs, and policies. Fair treatment means that no

racial, ethnic or socioeconomic group should bear a disproportionate share of the negative environmental consequences resulting from the operation of industrial, municipal, and commercial enterprises. Often the victims of these injustices live where contaminants have been transferred from the source. These people did not benefit from the products, which produced the pollutant. Planting trees *in situ* is a human-installed strategy that also leaves a legacy of clean air, soil, and water on the sites for future generations.

## **5. Discussion and summary**

### **What is different about the concept of connecting pollutant treatment with biomass growth compared to traditional short rotation woody crops?**

Plants played an important role in pre-human settlement ecology – transforming inorganic nutrients along with water and carbon dioxide into the oxygen, proteins, and other foodstuffs basic to the food web. Plants with associated microbes naturally perform these transformations on both natural and man-made compounds.

Many plants transform “pollutant” decomposition into the raw inputs for their growth; this process is basic to cycling of essential elements through the ecosystem. Thus, energy fluxing through the plant ecosystem, captured by the process of photosynthesis, is how plant cells grow and are sustained.

Phytoremediation takes advantage of the basic plant biochemistry by increasing the root zone reaction capacity of the plants. Certain plants are known to break down and detoxify many waste products of humans. Phytoremediation occurs when these compounds are considered ‘pollutants’, and the natural breakdown processes develop according to an environmental design for cleanup. Ultimately, phyto can play a role as a filter, cap, and reactor for decreasing environmental insults now

perpetrated by farming, industry, and urban life. Thus, we can design a plant system that will take advantage of ‘selected plants’ phytoremediation capabilities for the benefit of the environment while providing biomass economic benefits.

### **What is required for Phytoremediation Installations to fulfill environmental outcomes?**

For phyto to work, the plants need to grow vigorously and be healthy. There are steps on an important timeline for most phyto installations:

1. Site assessment and installation plan: Learn what chemical concentrations are in the soil by inspecting past site activities, available data, well sample analyses, and conduct soil sampling. Then, develop a soil, water, and plant management plan. It may be necessary to turn down inappropriate projects. Understanding plant physiology creates operating limits, such that many sites may not be candidates for phyto because of uneconomical site preparation needed to decrease a toxic compound, (i.e. sodium or boron).
2. Site preparation: The soil or growing medium of the site is where pollutants, soil amendments, plant roots, nutrients, water, and soil gas meet. Soil phytotoxicity can cause plant death or slow growth. Plant growth limitations such as salinity, petrochemicals, excess nutrients, compaction, high water tables, and droughty conditions are usually manageable through irrigation, drainage, soil removal, surface ripping, soil addition, mineral fertilization, and compost application.
3. Plant selection and installation: Plant selection will vary with phyto applications. Phyto is subject to the same climatic, soil, and time constraints facing

foresters, farmers, and gardeners around the globe. Phyto must also take into account root depth and vigor. In many current phyto installed locations, phytoremediation is accomplished by poplars, willows and grasses in the early phase of cleanup. Over time these sites will often evolve through succession into more diverse, long-lived native vegetation.

4. Environmental engineering plan: Phyto systems are often developed under a strict permit issued by a governmental regulatory agency. Permits detail engineering tasks required for monitoring, road construction, storm water drainage, and erosion control. Such tasks must be coordinated with a phyto management program, because plants such as trees are not portable.

5. Plant management plan: Plants requires water, penetrable soil, nutrients, weed control, pest control, and adequate drainage to grow well. Tree phyto sites require a forest management plan rather than short term engineering operation and maintenance plans driven by short-term economics to finish quickly. Foresters traditionally think in terms of 40 to 100 year time frames for a successful crop. Many of the pollutants treated by phyto also have long-term time lines when treatment is under ambient climatic conditions. Growth measurements are essential to monitor patterns of growth and survival and should be part of the management plan.

6. Harvest plan: Phyto is different from other pollutant treatment systems that may have only one specific outcome – there can be a planned harvest of biomass with phyto systems and/or an aesthetic or recreational use. And when harvest comes after the plants have performed their phyto role, the potential exists for harvesting value-added products described above.

Ultimately, plants help humans cycle wastes back into raw resources. It is hard to imagine a cyclic world where any waste would require an exit strategy into a new

product or into the raw inputs for soil, plants, and animals. Phyto offers a beginning to this design approach for cyclic living.

## 6. References

- 1) Mitchell, CP, Ford-Robertson, JB, Hinckley, TM, Sennerby-Forsse, L. Ecophysiology of short-rotation forest crops. New York, New York, USA. Elsevier Applied Science 1992. 308 pp.
- 2) Balatinecz, JJ, Kretschmann, Leclercq, A. Achievements in the utilization of poplar wood – guideposts for the future. *Forestry Chronicle* 2001, 77(2) 265-269.
- 3) Sennerby-Forsse, L, Christersson, L. The role of energy forestry in alternative energy planning, waste recycling, and agriculture in Sweden. *World Resource Review* 1994, 6, 395-405.
- 4) Gordon, JC. Poplars: Trees of the people, trees of the future. *Forestry Chronicle* 2001, 77(2), 217-219.
- 5) Licht, LA. Deep-rooted poplar trees grown in the riparian zone for biomass production and non-point source pollution control. 1990 Ph.D.Thesis, University of Iowa, Iowa City, Iowa, USA.
- 6) Licht, L, Aitchison, E, Schnabel, W, English, M, Kaempf, M. Landfill capping with woodland ecosystems. *Practice Periodical of Hazardous, Toxic and Radioactive Waste Management*, ASCE. 2001. 5(4) 175-184.
- 7) US Environmental Protection Agency. A citizen's guide to phytoremediation. EPA – 542-F-98-011, Office of Solid Waste and Emergency Response. Washington DC. 1998. 6pp.
- 8) US Department of Agriculture. Conservation buffers work – economically and environmentally. Program Aid 1615. Washington, D.C. 2000. 4pp.

- 9) Aronsson, P, Perttu, KL. Willow vegetative filters for municipal wastewaters and sludges. A biological purification system. Report 50 Swedish University of Agricultural Sciences, Uppsala, Sweden 1994. 230pp.
- 10) Westphal, LM, Isebrands, JG. Phytoremediation of Chicago's brownfields – consideration of ecological approaches and social issues. Proceedings Brownfields 2001 Conference, Chicago, Illinois, USA, 2001. BB-11-02.
- 11) Schultz, RC, Colletti, JP, Isenhardt, TM, Simpkins, WW, Mize, CW., Thompson, MI. Design and placement of a multispecies riparian buffer strip system. *Agroforestry Systems* 1995, 29, 201-226.
- 12) Iowa State University Extension. Stewards of our streams – buffer strip design, establishment, and maintenance. 1997. PM 1626b. Ames, Iowa, 6pp.
- 13) Perttu, KL. Environmental and hygienic aspects of willow coppice in Sweden *Biomass Bioenergy* 1999, 16(4), 291-297.
- 14) Dickmann, DI, Isebrands, JG, Blake, TJ, Kosala, K, Kort, J. Physiological ecology of poplars. In: Dickmann, DI, Isebrands, JG, Eckenwalder, JE, Richardson, J (Eds). *Poplar Culture in North America*. Ottawa, Ontario, Canada. NRC Research Press, 2001. p. 77-118.
- 15) Van Den Bos, Amelie. Phytoremediation of Volatile Organic Compounds in Groundwater: Case Studies in Plume Control. US EPA Office of Solid Waste and Emergency Response. 2000. [www.clu-in.org](http://www.clu-in.org).
- 16) Isebrands, JG, Karnosky, DF. Environmental benefits of poplar culture. In: Dickmann, DI, Isebrands JG, Eckenwalder, JE, Richardson, J. (Eds). *Poplar Culture in North America*. Ottawa, Ontario, Canada. NRC Research Press, 2001. p. 207-218.
- 17) Elowson, S. Willow as a vegetative filter for cleaning of polluted drainage water from agricultural land. *Biomass Bioenergy* 1999, 16, 281-290.
- 18) Wilkinson, AG. Poplars and willows for soil erosion control in New Zealand. *Biomass and Energy* 1999, 16, 263-274.
- 19) Licht, LA. *Salicaceae* family trees in sustainable agroforestry, *Forestry Chronicle*, 1992, Vol. 68(2), 214-221.

- 20) Licht, LA, Schnoor, JL, Nair, DR, Madison, MF. Ecolotree Buffers for controlling non-point sediment and nitrate, Paper and presentation, 1992. American Society of Agricultural Engineers, Nashville, Tennessee, USA.
- 21) US Department of Agriculture, Farm Bill 2002. [www.usda.gov/farmbill](http://www.usda.gov/farmbill)
- 22) U.S. Environmental Protection Agency, Design and construction of RCRA/ERCLA final covers, EPA/625/4-91/025, Eastern Research Group, Arlington, MA., 1991 pp. 1-13.
- 23) Aquino, J. Subtitle D: Compacting the year, Waste Age, November, 2001, p. 60 – 64.
- 24) Madison, MF, Licht, LA. Landfill cap closure utilizing a tree ecosystem, 1991, American Society of Agricultural Engineers, Albuquerque, New Mexico, USA.
- 25) Bolen, M, Roesler, A, Benson, C, Albright, W. Alternative cover assessment project, Phase 2 Report, September, 2001, USEPA #44-0000-2038.
- 26) US Environmental Protection Agency. Brownfields technology primer: Selecting and using phytoremediation for site cleanup, July, 2001, EPA542-R-01-006, July, 2001.
- 27) RMT, Inc. Operation, maintenance, and monitoring report for phytoremediation and natural attenuation for Ashland Chemical, Inc., Milwaukee Site, January, 2002.
- 28) Evergreen Magazine. What can we make from smaller trees? Bigfork, Montana, Summer 2002. p.14-15. ([www.evergreen](http://www.evergreenmagazine.com) magazine.com)
- 29) Licht, LA. Ecolotree Buffers for renewable biomass fuels, Paper and presentation, 1992. American Society of Agricultural Engineers, Nashville, Tennessee, USA.
- 30) Tuskan, GA, Walsh, ME. Short rotation woody crop systems, atmospheric carbon dioxide, and carbon management: A U.S. case study. Forestry Chronicle 2001, 77(2) 259-264.
- 31) Balatincez, JJ, Kretschmann, DE. Properties and utilization of poplar wood. In: Dickmann, DI, Isebrands, JG, Eckenwalder, JE, Richardson, J (Eds). Poplar culture in North America. Ottawa, Ontario, Canada. NRC Research

Press 2001. p. 277-291.

- 32) Hall, RB, Hilton, JD, Maynard, CA. Construction lumber from hybrid aspen plantations in the Central States. *Journal of Forestry* 1982, 80, 291-294.
- 33) Kretschmann, DE, Isebrands, JG, Stanosz, G, Dramm, JR, Olstad, A, Cole, P, Samsel, J. Structural lumber properties of hybrid poplar. USDA Forest Service Research Paper FPL-RP-573, 1999. 8pp.
- 34) Nelson, ND, Sturos, JA, Fritschel, PR, Satter, LD. Ruminant feed stuff from commercial foliage of hybrid poplars grown under intensive culture. *Forest Products Journal* 1984, 34, 37-44.
- 35) Allamaras, RR, Wilkins, DE, Burnside, OC, Mulla, JD. Agricultural technology and adoption of conservation practices. 1998. Ann Arbor Press, Chelsea, Michigan, USA. pp.99-158.
- 36) Marquez, CO, Cambardella, CA, Isenhardt, TM, Schultz, RC. Assessing soil quality in a riparian buffer by testing organic matter fractions in central Iowa, USA. *Agroforestry Systems* 1999, 44, 133-140.
- 37) Haycock, NE, Pinay, G. Groundwater nitrate dynamics in grass and poplar vegetated riparian buffer strips during winter. *Journal Environmental Quality* 1993, 22, 273-278.
- 38) O'Neill, G, Gordon, A. The nitrogen filtering capability of Carolina poplar in an artificial riparian zone. *Journal Environmental Quality* 1994, 23, 1218-1223.
- 39) Kuhn, GA, Josiah, SJ. Timberbelts: windbreaks that enhance production and produce profitable wood products. USDA General Technical Report 2000. N215 St. Paul, Minnesota. p.101.

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