SPATIAL AND TEMPORAL GROWTH TRENDS OF POPLAR TREES PLANTED FOR THE PURPOSE OF PAH REMEDIATION

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Abstract

The objective of this study was to investigate the spatial and temporal trends of a phytoremediation system comprised of poplar trees designed to control groundwater flow and remove primarily polycyclic aromatic hydrocarbons (PAHs). Several lab and field studies have demonstrated the success of poplar trees in effectively decreasing concentrations of volatile hydrocarbons, but few have demonstrated effects on PAH concentrations. Thus, the focus of this report will be the response of the poplar trees in relation to hydrophobic, nonvolatile polycyclic aromatic hydrocarbons (acenapthene, acenapthylene, anthracene, chrysene, fluoranthene, naphthalene, phenanthrene, and pyrene) in a shallow, surficial aquifer. This field study was conducted on a 1.7-acre site in Oneida, Tennessee contaminated with creosote that was once used for railroad cross-tie treatment. Spatial analysis was used to divide the site into areas based on contaminant levels and a layer of coal that served as a layer of low permeability at an approximate depth of 2 feet. The semi-impermeable coal layer does have an adverse impact on tree growth, while the contamination does not appear to adversely affect tree growth. The rate of growth is also impacted by the age of the tree at planting where younger trees grow faster than the older trees. A steady decrease in PAH concentrations has occurred at the multi-level samplers surrounded by a root zone that has penetrated the contamination. PAH compounds present at relatively high concentrations in the soil and groundwater do not appear to affect tree growth to a greater or lesser extent than lower PAH concentrations. While further research is required to affirm the positive effects of poplar trees at this site, the tree stand has responded well to the high PAH levels.

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1.0 Introduction

Phytoremediation is the use of plants and/or trees to control the movement of and reduce concentrations of soil and/or groundwater contamination. Inorganic contaminants can serve as nutrients absorbed by the plant's root system, and field and lab studies have supported the effectiveness of phytoremediation. Two ways in which plants aid in the control and remediation of contaminants are phytodegradation and phytostabilization. Phytodegradation involves the conversion of pollutants into a nontoxic form through plant transpiration; and phytostabilization implicates the pollutants are absorbed or entrapped in plant tissue or the soil matrix, thereby preventing the migration of the contaminant (Cunningham, 1995). Stabilization reduces or eliminates environmental concerns by immobilizing the plume through sorption into the soil and/or plant roots. Studies indicate significant biological activities in the root and in the shoot can be exploited for phytoremediation (Cunningham, 1995; Chaineau, 2000). Soil texture, pH, salinity, pollutant concentrations, and the presence of other toxins must be within the limits of plant tolerance (Cunningham, 1995). Phytoremediation is also potentially more cost effective and requires less maintenance than conventional methods.

Living plant roots can significantly impact physical, chemical, and biological properties of the soil (Chaineau, 2000). The general limitation of phytoremediation is that plants require oxygen, soil, water and nutrients (Cunningham, 1995), and not all sites will benefit from the same phytoremediation technology. The method of phytoremediation, whether it is grasses, trees, or a mix of the two, will depend upon site and contaminant characteristics. Due to growth and limited extent of plant roots, phytoremediation may be most appropriate in the case of large surface areas of relatively immobile contaminants close to the surface (Cunningham, 1995). Slowly moving contaminants will allow plants and trees the opportunity to become established before the contaminant has migrated beyond the tree stand.

Poplar trees have been proven as an effective enhancement of bioremediation. Field studies in Iowa, Oregon, and Slovenia have involved the use of poplar trees as a means of successfully reducing the toxicity of landfill leachate (Schnoor et al., 1995). In the lab, transpiration of BTEX compounds and trichloroethylene (TCE) to the surrounding atmosphere after translocation by plants has been established (Burken et al, 1998). These studies have tried to determine the mechanisms and pathways of phytoremediation. While these studies have focused on volatile compounds, evaluating poplar trees for the remediation of PAH compounds is the focus of the Oneida study. In addition, previous research has focused on the specific pathways or mechanism for removal of contaminants; but methods for evaluating the degree to which a system is working are lacking. The focus of this report is to develop methods that can be used to establish the degree to which a phytosystem is working. From this study, it is hoped that the limits and future possibilities of phytoremediation may be identified.

The objective of this research was to incorporate data collection from a phytoremediation study into a geographical information system to evaluate the effectiveness of poplar trees as a remediation technology for PAH compounds. As part of the Oneida study, groundwater contaminant levels, soil contaminant levels, and the heights and diameters of the poplar trees were collected over time. Combining these data will provide spatial and temporal variations in poplar tree growth with respect to contaminant levels. Site conditions and the methods of evaluating poplar tree growth as it relates to contaminant levels will be reviewed in the following pages. Upon completing this analysis, the growth response of poplar trees with regards to PAH compounds will be used to study the effectiveness and the feasibility of using poplar trees as an effective *in situ* method of remediation of PAH compounds. In addition, effects of an impermeable coal layer on tree growth will be investigated. Furthermore, the desired result of this study is to identify another means for monitoring the effectiveness and health of the phytoremediation system and provide a line of evidence to demonstrate phytoremediation is accomplishing contaminant reduction. The procedures and analyses performed in this report provide a potentially novel approach to determine whether or not phytoremediation is working. These procedures may be applicable to other sites containing PAH and non-PAH compounds, such as BTEX and TCE.

2.0 Background Information

2.1 *In situ* bioremediation of polycyclic aromatic hydrocarbons

Sites containing volatile aromatic hydrocarbons have dominated *in situ* bioremediation field experience (Brubaker et al., 1992). Those sites that have implemented phytoremediation as an option have experienced reduction in contaminant levels through plant/tree transpiration and increased microbial activity in the rhizosphere. Numerous processes including the use of supercritical flows, surfactants, triethylamine, liquid propane, kerosene, and organic solvents have been proposed for the extraction of hydrophobic contaminants, such as polycyclic aromatic hydrocarbons (PAHs), from soil. However, these treatments are generally intended for excavated soils (Kilbane, 1998). Concerns of increased ground water contamination due to mobilization of the contaminants and the fact the extractive agent itself can be a contaminant has limited the further development of *in situ* remediation of PAHs (Kilbane, 1998). The use of phytoremediation would eliminate possibilities of increased ground water contamination.

2.2 Characteristics of polycyclic aromatic hydrocarbons

Polycyclic aromatic hydrocarbon molecules contain only hydrogen and carbon atoms with two or more aromatic rings (Brubaker et al., 1992). PAHs form during incomplete combustion of organic materials and exhibit low volatility and low aqueous solubility (Mahaffey, 1991). Table 2.1 summarizes those properties important to the extraction and biodegradation of PAHs. As the number of rings and molecular weight increases, PAH properties possess a greater tendency to inhibit solubility and degradation. The solubility of PAHs in water, which relates to their ability to biodegrade, decreases as their molecular weight increases (Brubaker et al., 1992; Mahaffey, 1991; Zappi, 1996). Because of physical and chemical properties, PAHs have a high affinity for association with organic carbon material in soil (Kilbane, 1998). The tendency of PAHs to sorb to soil particles makes them less accessible for biodegradation and extraction. Thus, sorption has a higher impact on the extractability of PAHs than on the biodegradability of PAHs (Kilbane, 1998). Degradation rates for four- and five- ring

PAHs are ten to twenty times slower than those of BTEX and other low molecular weight compounds (Brubaker et al., 1992).

Table 2.1 - Chosen properties of selected polyaromatic compounds (Brubaker and Stroo, 1992)

Compound	Number of Rings	Molecular Formula	Solubility (mg/L)	K_{OC}	Biodegradation half-life (days)
Benzene	1	C_6H_6	1780	85	5-10
Napthalene	2	$C_{10}H_8$	30	2300	9-13
Anthracene	3	$C_{14}H_{10}$	0.045	18000	<9-50
Phenanthrene	3	$C_{14}H_{10}$	1.0	18000	<6-43
Pyrene	4	$C_{16}H_{10}$	0.132	38000	
Chrysene	4	$C_{18}H_{12}$	0.0018	2×10^5	41-116
Benz[a]anthracene	4	$C_{18}H_{12}$	0.0057	1.38×10^6	63-231
Benzo[a]pyrene	5	$C_{20}H_{12}$	0.0012	5.5×10^6	

The *in situ* bioremediation of PAHs relies on the enhancement of native bacteria that use the contaminants as a source of carbon and energy (Brubaker et al., 1992). The greatest influence on PAH biodegradation is soil moisture, pH, inorganic nutrients, loading rates, initial PAH concentration, and microbial population (Mahaffey, 1991). The limited bioavailability of PAHs results in poor desorption capabilities that may be critical to the lack of degradation. (Zappi et al., 1996). Once PAHs are dissolved, bacteria can provide continued depletion of PAH constituents (Brubaker et al., 1992). While the general limitation of the degradation of volatile aromatic hydrocarbons is oxygen transport, many studies have suggested the limiting factors of PAH degradation are mass transfer and bioavailability (Brubaker et al., 1992; Kilbane, 1998; Mahaffey, 1991; Zappi, 1996).

2.3 Remediation of PAH compounds using Poplar trees

Very few studies have been undertaken or published quantifying the effects of plants or trees on hydrocarbon removal (Chaineau, 2000). Poplar trees were selected for remediation at the Oneida, Tennessee site. Poplar trees are classified as phreatophytes, which, by definition, means they “depend for their water supply upon ground water that lies within reach of their roots (Robinsion, 1981).” Poplar trees are commonly used as phytoremediation tools because they are perennial, hardy, tolerant of high concentrations of organics, highly tolerant of flooding, fast growing, easily propagated, and have a wide range of adaptation (Jordahl, 1997). The function of poplars in regards to phytoremediation can be described in two ways: (1) uptake of pollutants through sorption and biodegradation in the rhizosphere, and (2) the “control” of groundwater flow.

Trees and plants indirectly aid in the control and degradation of pollutants by facilitating the growth of microorganisms around the root zone, i.e. the rhizosphere zone (Jordahl, 1997). Biodegradation of smaller compounds can induce microbes to produce enzymes that can degrade complex compounds (Mahaffey, 1991). The influx of microorganisms in the vadose zone allows for a greater consumption of organic material during microbial metabolism. However, most microorganisms found in the rhizosphere cannot tolerate as high of concentrations as those tolerated by plants (Schnoor et al., 1995).

Mackay’s (2000) experiment testing the sorption capabilities of various samples of Douglas fir and Ponderosa pine on aqueous benzene, toluene, and o-xylene concentrations suggests the possibility of contaminant transport through wood by sorption. Research indicates poplars demonstrate a high level of translocation of non-PAH compounds to leaves without showing signs of phototoxicity (Burken, 1996). When exposed to atrazine in a hydroponic environment, poplar cuttings showed “no visible signs of toxicity or depressed transpirations rates” in the short term, but it is thought long term exposure may cause toxicity (Burken et al., 1998). Further studies with cuttings from the hybrid poplar tree, *Populus deltoides X P. trichocarpa,* showed that TCE was not toxic to the trees, even at concentrations much higher than those usually found at hazardous waste sites (NIEHS/EPA Superfund Basic Research Program, Research Brief - Number 16). The apparent successes of poplars' ability to transpire organic contaminants and oxygenate the rhizosphere render them a positive defense against contamination.

2.4 Evidence of PAH degradation

Despite the limited research involving the *in situ* treatment of PAH compounds, several studies have indicated successful treatment of PAHs in the cases of post-treatment of excavated soil and hydroponic environments. In these situations, the optimal environment for PAH degradation can be manipulated and maintained. Successful biodegradation rates (over 90%) of three- and four- ring PAHs have been achieved in drum bioreactors and slurry reactors (Woo, Seung Han et al., 1999; Zappi et al., 1996). Contaminant reductions of 93% in groundwater samples, 80% in saturated soils, and 66% in unsaturated soils were observed when soil samples in the lab received nutrient growth factors and a surfactant (Mahaffey, 1991).

Liste performed experiments on the basis that plants releasing high concentrations of phenol may be useful for phytoremediation of soils because the phenol fosters growth of PCB-degrading bacteria. While degradation was experienced, the reasons for decreases in concentrations of phenanthrene could not be distinguished between plant enzymes, microbial activity, or the root surface (Liste et al., 1999). Liste did observe that though corn had the greatest root mass, it had the least effect on concentration of phenanthrene (Liste et al., 1999).

Chaineau observed higher degradation rates in aromatic hydrocarbons in early stages of maize growth; however, the significant process appeared to be rhizosphere degradation and not direct uptake of the hydrocarbons. Degradation decreased as maize growth, which was restricted by the size of the containers limiting root development and not nutrient shortening, decreased (Chaineau, 2000).

Zappi (1996) observed PAHs of greater than 3 rings generally did not show significant biodegradation. While it was hypothesized that disappearance of primary carbon and energy sources was the reason for slowed degradation, a further supply of a growth and an energy source did not improve degradation (Zappi et al., 1996). Mahaffey observed a similar response in a lab study using soil columns. The soil columns showed no further reduction in PAH levels after additional oxygen was provided (Mahaffey, 1991). These results implicate bioavailability as the limiting factor of PAH degradation, and studies suggest that bioavailability may not be an issue at high concentrations (Kilbane 1998; Zappi, 1996).

3.0 Description of Study Area

The study area is located in Scott County, Tennessee in the central portion of the northern edge of the Cumberland Plateau (Geraghty and Miller, 1997). This portion of Tennessee is characterized by "gently dipping strata" to the east and structural features of the plateau are small and limited local areas (Geraghty and Miller, 1997). The ground surface across the site is at an elevation of approximately 1430 feet above means sea level. The aquifer consists of a layer of sand overlain by a layer of sandy clay with bedrock of shale approximately ten feet below the land surface. Surficial soils range in thickness between 8 and 12 feet and are comprised of interbedded yellow-brown to orange-brown, silty clays with underlying unconsolidated sand which is grey and orange in color (Geraghty and Miller, 1997). The surficial aquifer is underlain by shallow bedrock, comprised mostly of clastic material comprised of shale, siltstone, sandstone, conglomerate, coal, and thin discontinuous beds of impure limestone (Geraghty and Miller, 1997).

3.1 Study Site

The cross-tie treatment operations consisted of a cross-tie facility, creosote holding tank, treatment unit, holding pond, and rail-spur track (Geraghty and Miller, 1997). A leaking source of creosote was discovered to be contaminating a shallow, unconfined aquifer and into Pine Creek. Operations discontinued in 1973 and selected equipment was dismantled (Geraghty and Miller, 1997).

A monitoring program began in 1997 to access soil and groundwater contamination and to collect hydrologic data. The monitoring system consisted of 7 monitoring wells, 25 multi-level samplers, and 27 piezometers across the 1.7-acre site. Figure 3.1 presents the CAD drawing of the site, which includes the direction of groundwater flow, multi-level samplers, location of the contaminant plume, the creek, the trees and other pertinent features used for visualization and analysis. Groundwater levels indicate an average depth of six feet to the water table from the land surface plus or minus two feet due to seasonal variation. Nine polycyclic aromatic hydrocarbons, all constituents of creosote, were detected in soil and groundwater samples: acenapthene, acenapthylene, anthracene, chrysene, fluoranthene, naphthalene, phenanthrene, and

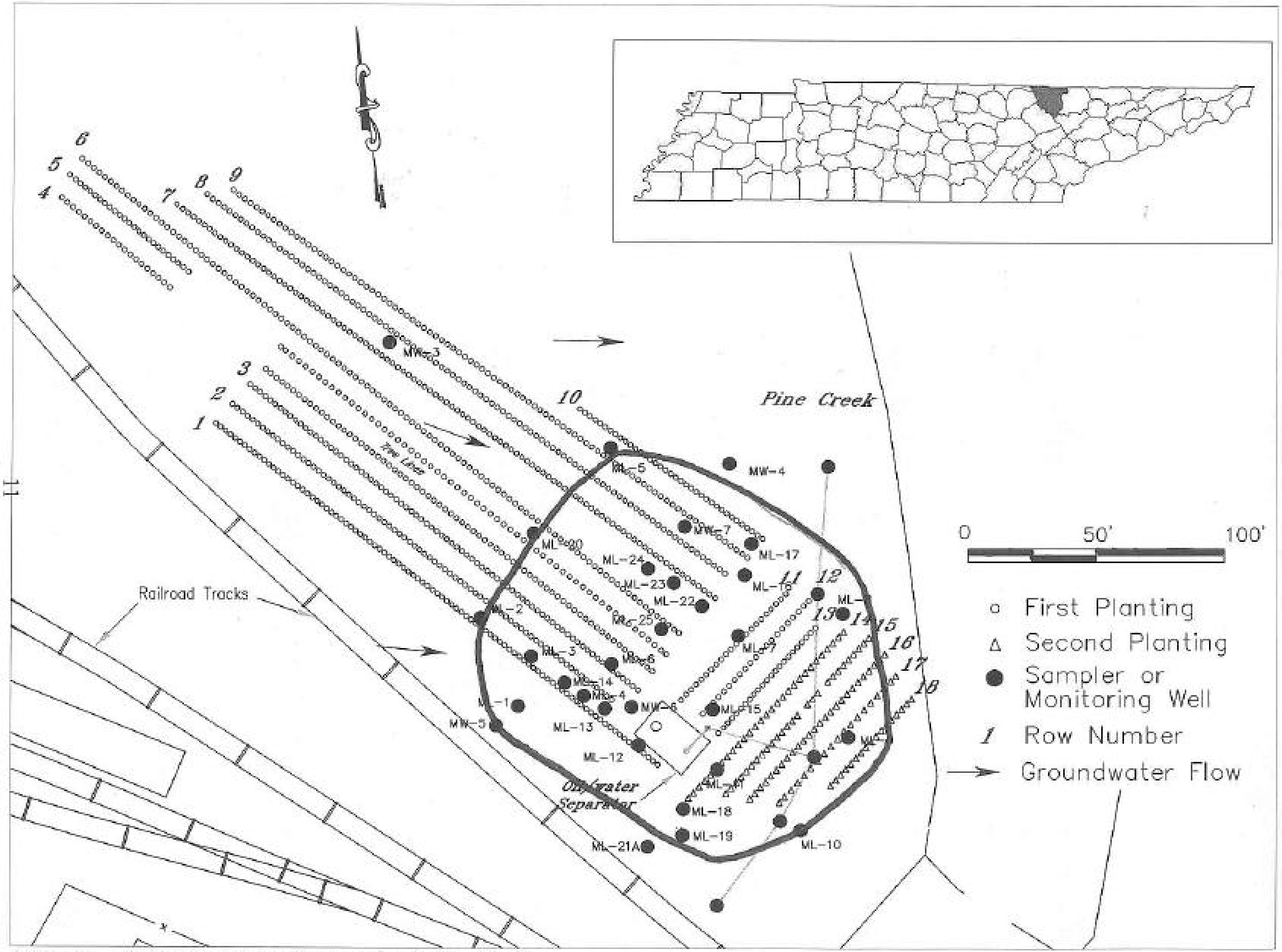


Figure 3.1 – Study site and location map for Oneida, TN site

pyrene. An interception trench was installed in March 1992 to prevent surface water contamination. In the fall of 1997, the trench was upgraded after it was found to no longer be working. A phytoremediation system was instituted in March of 1997, seven years after having discovered the contamination.

Low transmissivity, variations in hydraulic conductivity, and the nature of the contamination (DNAPL) prevented pump and treated from becoming an option. The shallow nature of the aquifer and the size of the site made it a candidate for phytoremediation. In the case of Oneida, PAH compounds, which are not readily volatilized, lay at the bottom of the shallow aquifer as an oily dense nonaqueous phase liquid (DNAPL). It is known that hardwoods grow well in Tennessee, and studies indicate the PAH concentrations are within poplar tree tolerance (Geraghty and Miller, 1997). Predation by cottonwood beetle and cutworm are concerns and were monitored by the consultant. The main objective of employing the phytoremediation system was to protect surface water quality of a nearby creek, protect off-site groundwater, and to protect future site workers (Geraghty and Miller, 1997). It is believed the trees will control the extent of the plume by uptake of on-site groundwater and by increases in the rate of PAH degradation through enhanced microbial growth and/or sorption. The means and methods used to evaluate contaminant levels, groundwater levels, and tree growth will contribute to determining whether or not these objectives were met.

3.2 Phytoremediation System

In March of 1997, thirteen rows totaling 916 hybrid poplars were planted approximately 2.5 feet apart in rows spaced 10 feet apart over approximately 0.6 acres (1726 trees/acre) in a manner illustrated in Figure 3.1 (Geraghty and Miller, 1997). Rows 1-10 run southeast to northwest and rows 11-13 run southwest to northeast. In May 1998, rows 14-18 (120 trees), which parallel rows 11-13, were added for a total of 1036 trees. In Figure 3.1, circles denote the first planting and triangles denote the second planting. The density of the tree stand is less than two other poplar tree studies in which the trees were watered with leachate or wastewater. Previous studies have utilized tree densities ranging from 2170 trees/acre (Licht, 1994) to 12425 trees/acre (Erickson, 1994).

For purposes of monitoring Oneida tree growth, each row was numbered and each tree was given a number according to its position in a given row. The trees were 1-year old when they were planted with the exception of rows 3-5, which were 2-years old when planted. The average height of the 1-year old trees were assumed 3 feet tall upon planting and the average height of the 2-years old trees were assumed 6 feet tall upon planting. Periodical measurements of tree height and basal circumference were made.

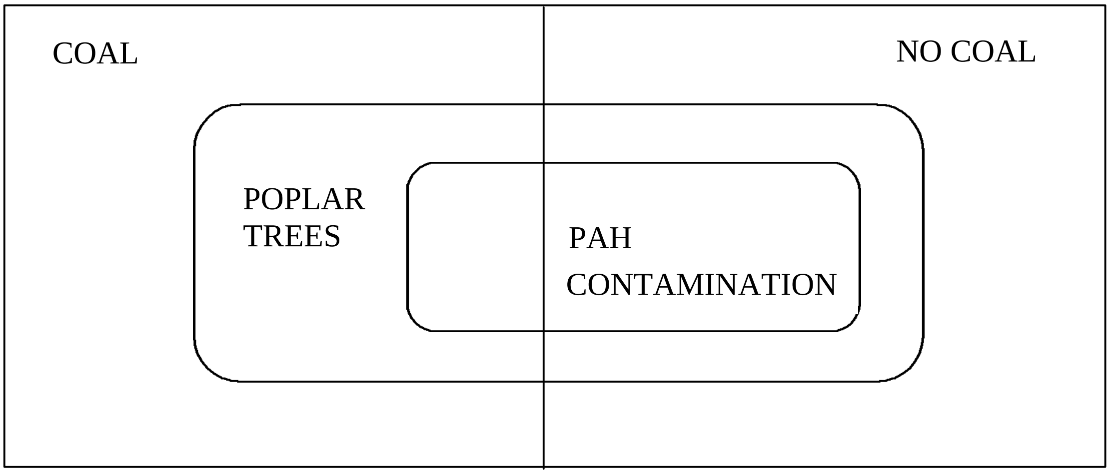
A layer of coal spread across the northeastern portion of the site years ago resulted in a 3- and 4-feet thick low permeable layer lying approximately eight to ten inches below the land surface. To prepare the site for the phytoremediation system, the site was cleared and grubbed, and silt fencing was installed for the purpose of erosion prevention (Geraghty and Miller, 1997). Three on-site soil stockpiles were spread across the site to create eight to ten inches of sand and gravel topsoil that was treated with fertilizer, ag lime, and manure (Geraghty and Miller, 1997). The three stockpiles were tested for contamination and were found to contain between 17.8 and 208.0 mg/kg of total PAHs and between 39.4 and 1060 mg/kg of total petroleum hydrocarbons (Geraghty and Miller, 1997).

After rototilling and trenching, the trees were planted over approximately 0.6-acres of the site. From this, it can be seen that approximately 40% of the trees were planted over contamination. A correlation of changes in PAH levels with depth at selected multi-level samplers and depth of root penetration will be investigated throughout the area of contamination. Those trees not planted over contamination were to provide a visual barrier for adjacent properties and to aid in water removal (Geraghty and Miller, 1997). A majority of these were planted directly over the layer of low permeability coal, which is thought to impact recharge and the depth to which the roots can penetrate.

3.3 Spatial Distribution of Trees

The unique nature of the Oneida site is the spatial variation in factors that may affect tree growth. Figure 3.2 gives a Venn diagram of the four spatial areas at the Oneida tie yard consisting of (1) contamination and coal, (2) contamination and no coal, (3) no contamination and coal, and (4) no contamination and no coal. It serves to simplify the site characteristics for better understanding of factors involved in tree growth.

Figure 3.2- Conceptual illustration of spatial variability within the phytoremediation system



Through this analysis of spatial variation, differences in tree growth between each area can be assumed to be dominated by one of these factors since all other factors are assumed to remain similar. The more dominant factor should be pinpointed through tree growth comparisons. Figure 3.3 depicts the location of these groups in relation to the site and each other. This illustrates the distribution of trees throughout the site in relation to contamination and the coal layer.

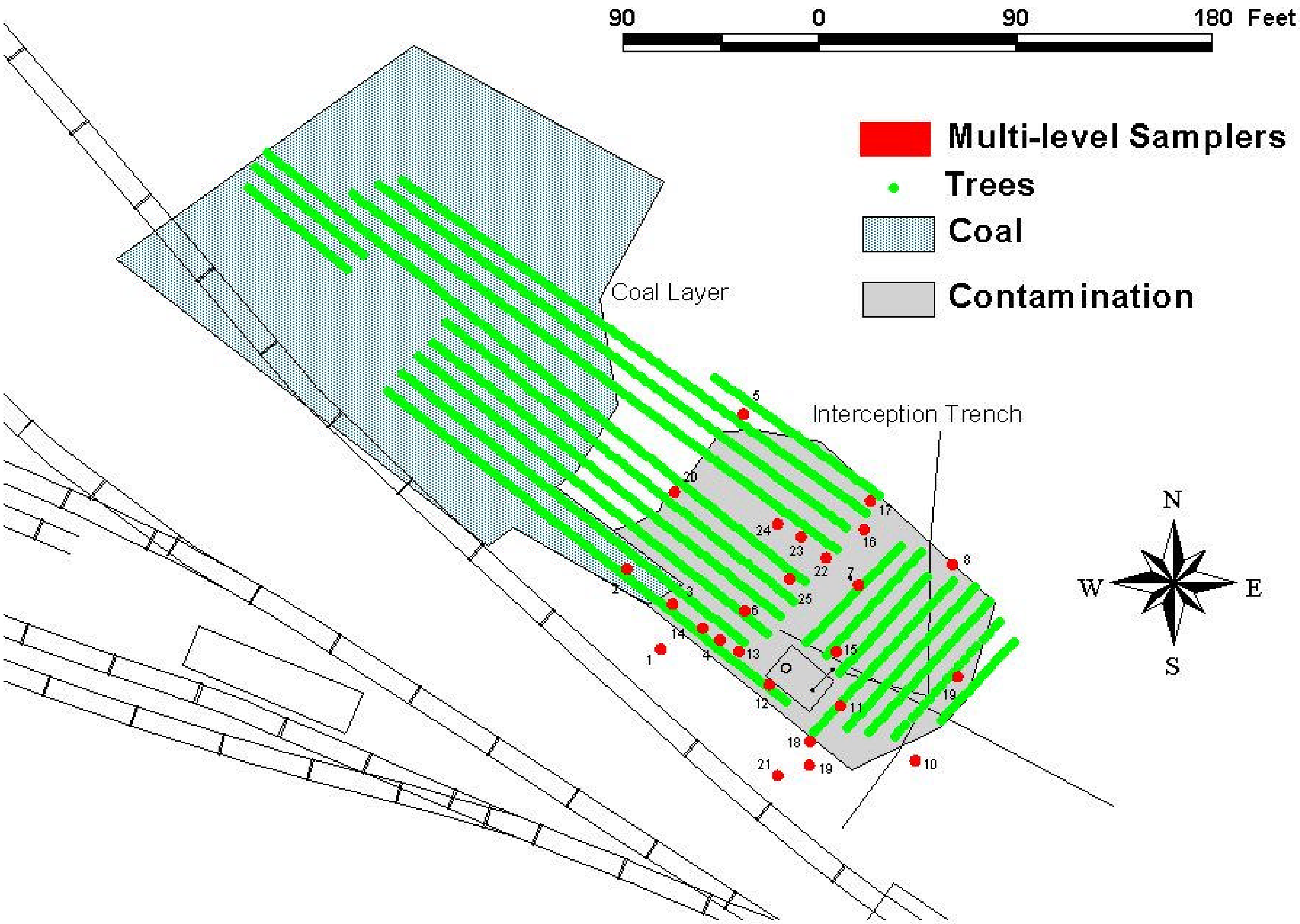


Figure 3.3 - Spatial areas used in analysis of height and growth of poplar trees

4.0 Method and Materials

An increasing number of Geographical Information System (GIS) tools have been identified and implemented for the purposes of spatial analysis. Risk analysis and response, hydrologic modeling, and earthquake research effectively utilize the capabilities of GIS. The use of GIS as a ground water monitoring tool has been limited. GIS development provides a more functional means of communication in order to provide for better management decisions. The greatest limit to the functionality of any GIS is the quality of data. The effectiveness of any spatial analysis will be enhanced as a result of good data collection.

In order to evaluate the spatial variation of the Oneida railroad site, a spatial analysis engine was employed. Spatial representations of contaminant and tree locations and tree growth will serve to visually illustrate any trends between tree height, growth, and contaminant concentration. A combination of the site wells, topography, soil and groundwater contaminant plume and tree measurements will allow the function of this GIS to include a spatial visualization of the site, representation of the root zone, vertical representation of contaminant, and illustration of tree growth. The study of groundwater contamination using GIS combines the already regular GIS uses in soil science, water quality, and hydrologic modeling.

4.1 Data Collection

Tree heights and basal circumferences were measured at different times of the years inside and outside of the growing season (growing season between April and October). The 1-year-old trees were assumed an average height of 3-feet upon planting and the 2-year-old trees were assumed an average height of 6-feet upon planting. A wooden pole marked at 1-foot increments and a Philadelphia rod marked at 0.1-foot increments were used to measured tree heights four different times since plantation - March 1998, June 1998, March 1999, and November 1999. In future study, a new method must be employed because some trees had reached the limits of current measuring techniques. The heights of the trees within the aforementioned spatial groups were compared based on percent growth and total growth.

The circumferences of the trees were also measured four different times - June 1998, December 1998, May 1999, and November 1999. No assumptions were made regarding the diameters of the trees when planting occurred. The circumferences were measured 1-foot (0.3 meters) from the base of the tree with a measuring tape. The slender nature and young age of the poplars allowed for some error in the position of the measurement without compromising the integrity of the data. The circumferences of the trees within the aforementioned spatial groups were used to compute total basal area and changes in basal area when tree competition was investigated.

Contamination levels in soil and groundwater samples were analyzed by numerous Virginia Tech investigators. Groundwater samples were acquired from as many multi-level samplers as possible during sampling periods. Dry conditions during some sampling periods limited groundwater data collection. Soil samples were acquired from soil borings taken along selected transects. Concentrations of the nine constituents of creosote (acenapthene, acenapthylene, anthracene, chrysene, fluoranthene, naphthalene, phenanthrene, and pyrene) were measure in the Virginia Tech Environmental Engineering Laboratory. The pH and concentrations of nitrate, nitrite, dissolved oxygen, Iron (III), and sulfate were also measured. These data were used to examine contaminant levels and dissolved oxygen levels with respect to the root zone depth, which was related to tree height.

4.2 Data Analysis

CAD drawings of the site in conjunction with the spatial analysis engine ArcView were important factors for examining spatial growth patterns. The trees, the multi-level samplers, the coal layer, and key features of the site were imported into ArcView from a CAD drawing to begin the analysis. A database containing height and growth information for each tree was attached to the tree shapefile for spatial growth analysis. Groundwater contamination data was linked to each multi-level sampler to examine concentration levels in certain areas of trees.

4.2.1 Analysis between Spatial Divisions

Average heights and diameters of each spatial division were computed to establish limiting growth factors throughout the site. Tree health was assumed to be associated with tree height, tree growth, and basal growth. When total and percent changes in tree height and circumference were computed between the measurement periods, some negative values were obtained. Presumably, errors such as these are due to measurement errors and these values were disregarded during the analysis. However, if a tree died, the average total and average percent growths were affected by counting that tree as having zero total or percent growth.

Survivor basal area growth is calculated as the change of basal area of trees, which have survived since the last measuring period. Net basal area growth is calculated as survivor growth minus the loss of basal growth due to tree death (DeBell et al., 1997). A tree competition index was calculated by summing the product of basal diameter and height at measurement periods (DeBell et al., 1997). The competition index is an approximation of the woody biomass within a tree stand that requires nutrition. Plotting basal growth versus the competition index allowed for a growth comparison of the spatial areas during periods of similar competition. This will be helpful in determining if the natural thinning process or some other factor is controlling poplar mortality. If each spatial area exhibits similar growth rates at similar competition indices, then it may be inferred that the contamination and/or coal do not adversely impact tree growth.

Percent growth of different aged trees was compared as well. Younger trees tend to grow at a faster pace (DeBell, 1997). Thus, it is of interest to see if the younger trees do grow faster and if higher degradation rates are noticed because of this. Further investigation could lead to evaluating the efficiency of the phyto system as time increase based on the age of the tree stand.

4.2.2 Analysis of Contamination Effects

To examine the effects of the contamination on tree height, nine multi-level samplers (ML-3, ML-4, ML-5, ML-7, ML-8, ML-11, ML-12, ML-13, and ML-20) were selected to provide adequate site coverage. Three samplers (ML-5, ML-8, and ML-20) fall outside the area of contamination and the remaining samplers lie within the area of contamination. A randomly chosen buffer of radius 10 feet was established around each of the selected multi-level samplers in ArcView. The buffer was then used to clip the surrounding trees to establish which trees lay within each buffer. These trees were considered the most effected by contamination found in the associated multi-level sampler. The average, minimum, and maximum height of the selected trees was then found. Using the 1/3rd-height rule identified by the consultant, the depth of root penetration could be estimated for each group of trees.

Another analysis was performed on the trees within the area of contamination. The trees were divided into six different areas based upon the maximum groundwater contamination concentrations over which the lay. It is of interest to determine whether varying concentration of PAHs had any effect on tree growth. The trees within the contamination were further subdivided according to concentrations over which they lay. Thus, the contaminant plume was divided into six areas of varying maximum concentrations. Tree growth was evaluated within each of these areas to determine whether or not higher concentrations of PAHs limited tree growth. Finally, tree growth at the Oneida site was then compared to other poplar tree growth studies**.**

5.0 Results and Discussion

5.1 Use of Visualization Tools

Analyzing variations in contaminant concentrations and tree heights requires the use of software capable of spatial analysis. Yet, software specialized for groundwater and contaminant modeling would benefit the visualization of temporal and vertical trends in contaminant concentration. A complete analysis was attempted using the spatial analyst engine ArcView and then the groundwater modeling program GMS. However, neither programs provided the tools needed for a complete and satisfactory analysis.

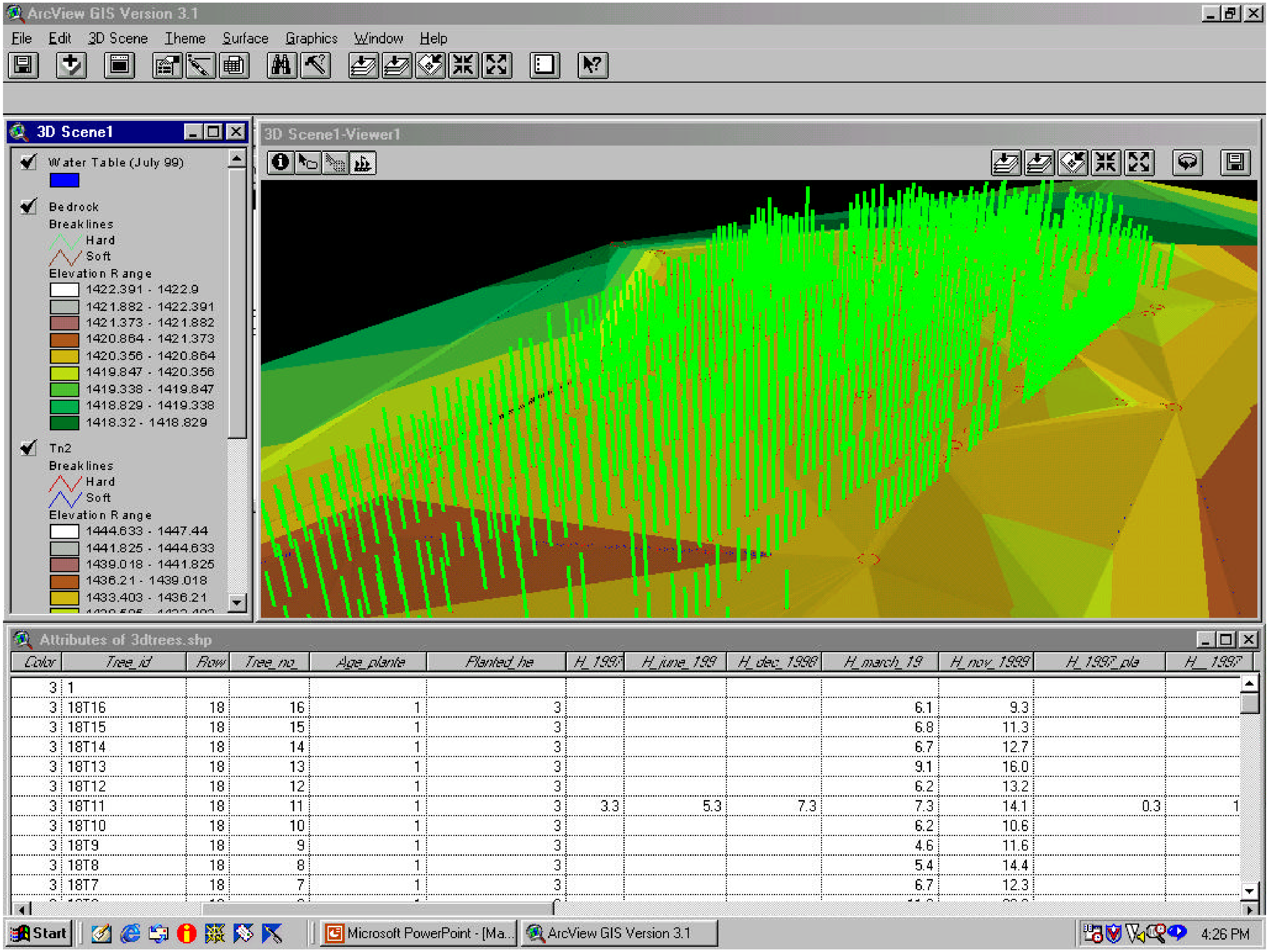
5.1.1 ArcView

ArcView allows for the use of database information to describe an entity. For example, tree data and multi-level sampler data collected in the field may be associated with graphical representations of the trees and samplers. This allows the user to query and highlight areas exuding some predefined criteria defined by the user, whether that condition is tree height, tree growth, or contamination. Areas of similar properties may then be displayed for a visualization of site heterogeneities. Attempts to explain these heterogeneities can then be hypothesized based on some other parameter.

Figure 5.1 illustrates the combination of database and visualization capabilities of ArcView. Three-dimensional visualization of the trees (green bars) was accurate because actual heights based on field data were used to extrude the trees over a land surface TIN that also created in ArcView. Figure 5.2 illustrates the tree roots (red bars), water table, and bedrock in an ArcView 3D Scene. However, the representation of the plume, especially with respect to depth, was unacceptable using ArcView. The plume was represented in an areal extent as contour lines of equal concentration at each depth. The contour lines were crude and ineffective for visualizing vertical changes in contamination.

5.1.2 GMS

GMS models groundwater and contaminant movements based on a conceptual model input by the user. Field data such as soil borings and sampler data may also be placed into GMS. From multi-sampler contaminant data, a plume can be delineated



Color	Tree_id	Row	Tree_no_	Age_plante	Planted_he	H_1997	H_june_199	H_dec_1998	H_march_19	H_nov_1999	H_1997_pla	H__1997
3	1											
3	18T16	18	16	1	3				6.1	9.3		
3	18T15	18	15	1	3				6.8	11.3		
3	18T14	18	14	1	3				6.7	12.7		
3	18T13	18	13	1	3				9.1	16.0		
3	18T12	18	12	1	3				6.2	13.2		
3	18T11	18	11	1	3	3.3	5.3	7.3	7.3	14.1	0.3	1
3	18T10	18	10	1	3				6.2	10.6		
3	18T9	18	9	1	3				4.6	11.6		
3	18T8	18	8	1	3				5.4	14.4		
3	18T7	18	7	1	3				6.7	12.3		

Figure 5.1- Illustration of database and visualization capabilities of the phytoremediation system in ArcView

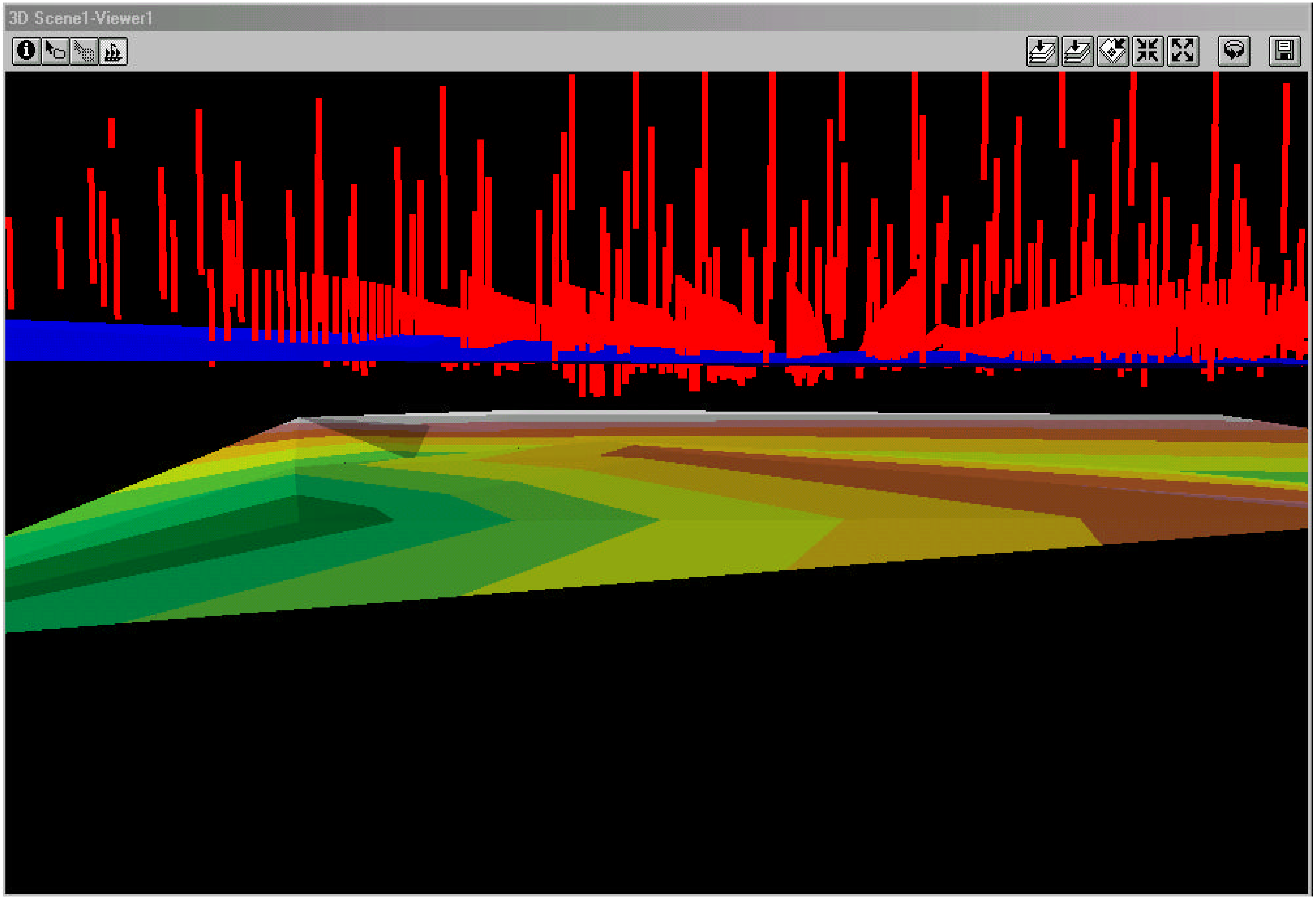


Figure 5.2-ArcView 3D-Scene of tree roots, water table, and bedrock

based in horizontal and vertical variations. Data collection over time results in a continuous representation of changes in the plume. Contamination data may be combined with a groundwater model to produce animation illustrating the changes in size, position, and concentration of the plume. However, GMS lacks the spatial capabilities of ArcView to relate areas of similar spatial characteristics to each other or the contamination. The superiority of plume visualization and movement provided by GMS combined with the spatial functions of ArcView would present the researcher with a powerful tool useful for phytoremediation study.

5.2 Comparisons of Tree Health between Spatial Areas

Growth rates in the four spatial areas (contamination and coal, contamination and no coal, no contamination and coal, no contamination and no coal) were compared to identify any growth trends that may illustrate the effects of the contamination and coal on tree growth. Trees planted to replace those trees that died were not included in the analysis. In March 1998, the maximum tree height was 10.2 feet and the average tree height was 5.5 feet. In March 1999, the maximum tree height was 19.5 feet and the average tree height was 9.2 feet. In November 1999, the tallest tree was measured to be approximately 29 feet, which was close to the limit of the measuring methods, and the average height of the poplar stand was determined to be 14 feet.

Figure 5.3 represents tree heights in November 1999 as gradually varied symbols sizes based on tree height. Larger circles indicate the taller trees at the site. The figure provides a general look into what areas across the site possess healthy trees. The larger trees appear in the areas of contamination and no coal. The smallest trees appear in the coal layer. The samplers are also shown to illustrate their location in relation to the spatial areas. Further analysis of each spatial areas is performed below.

Figure 5.4 highlights in blue those trees that have exhibited below average heights in November 1999. It illustrates the trees of average and above average height and the spatial areas in which they fall. Figure 5.5 highlights in magenta those trees that have experienced less than average percent growth based on percent difference in tree heights between March 1997 and November 1999. From figures 5.4 and 5.5, three distinct areas of reduced growth appear: (1) trees within the coal layer, (2) trees of 2-years when

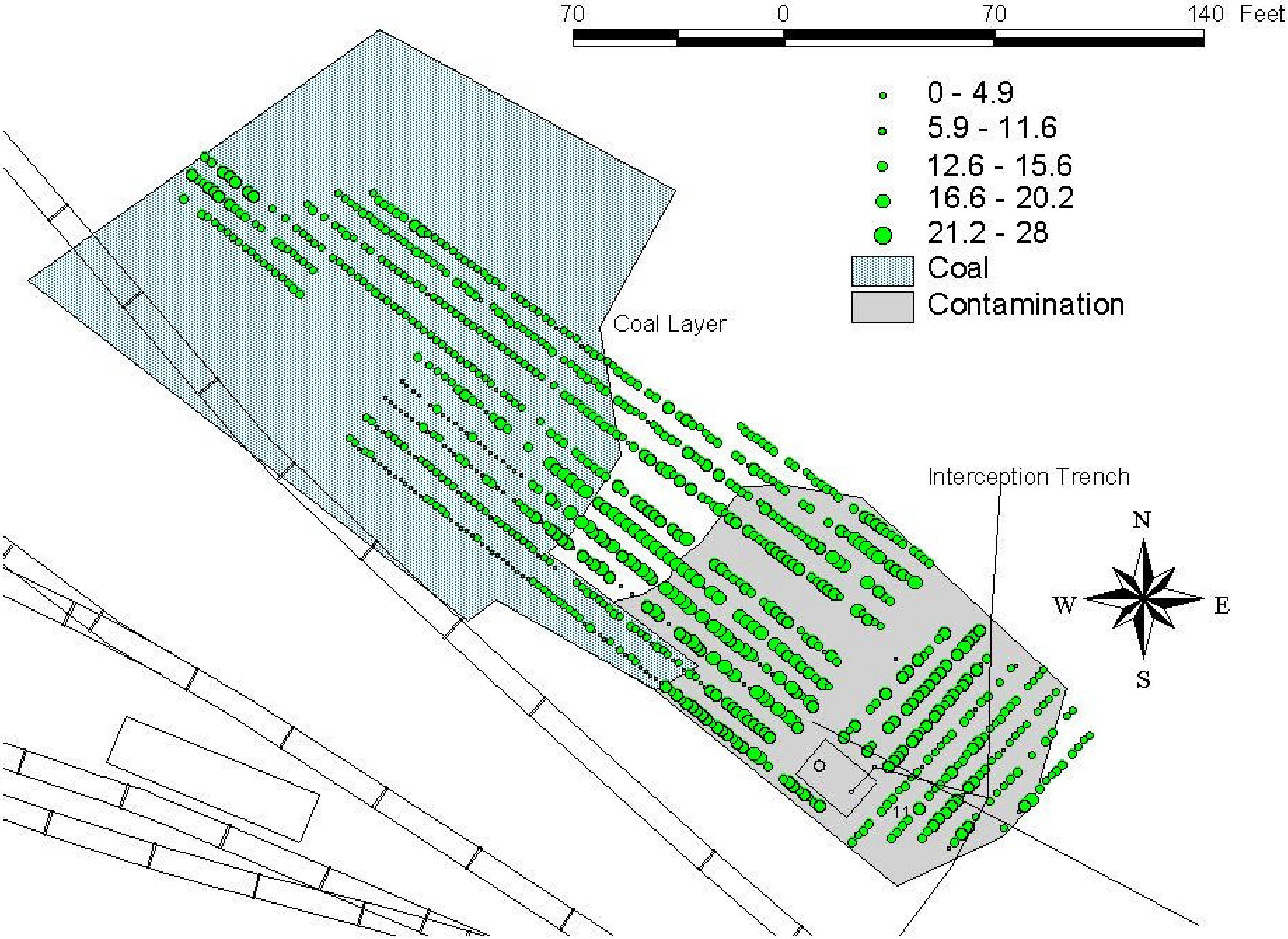


Figure 5.3 - Representation of tree height distribution using gradually varied symbology

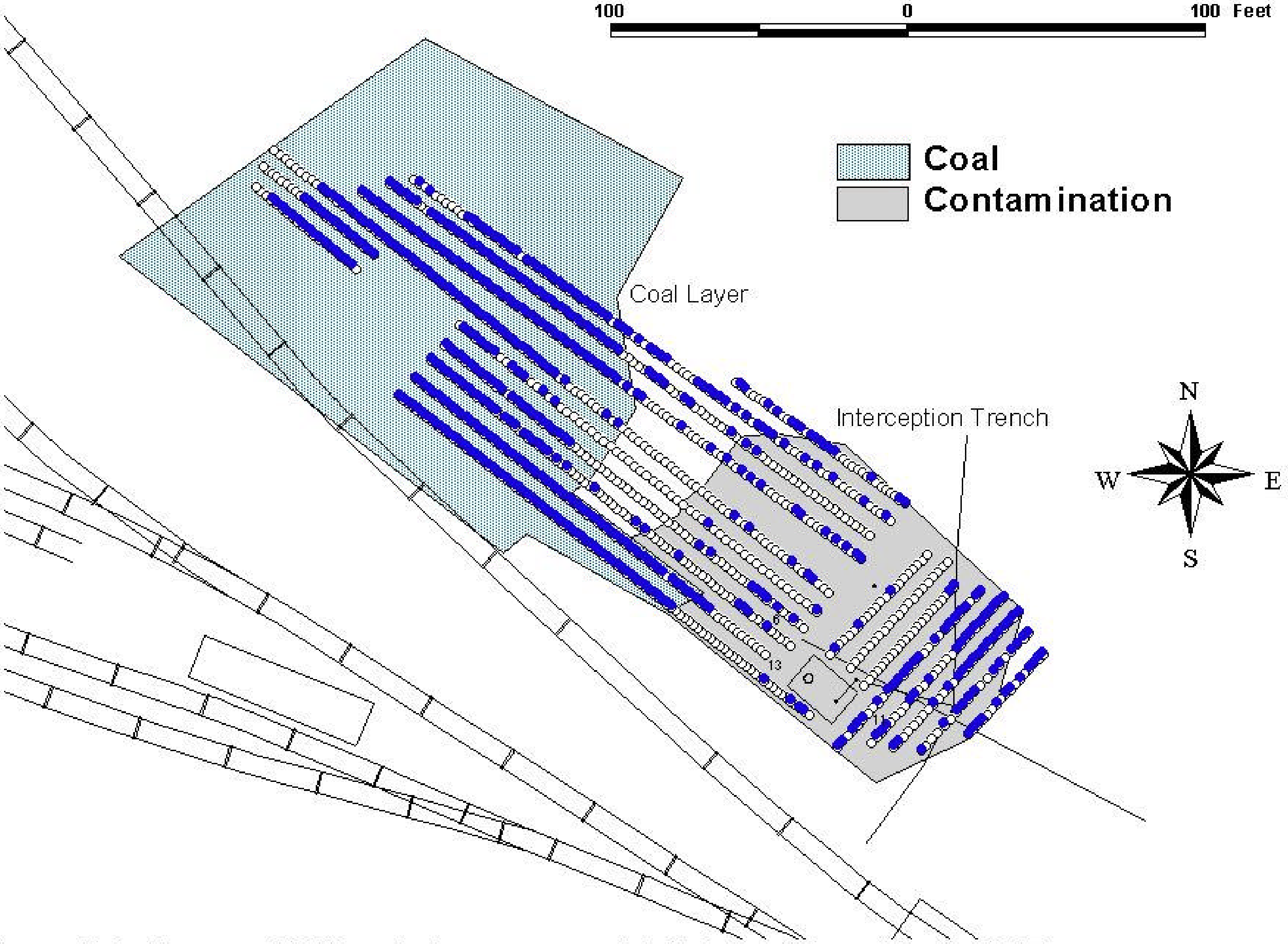


Figure 5.4 - Trees exhibiting below average (<14') height from March 1997 to November 1999 are colored in blue

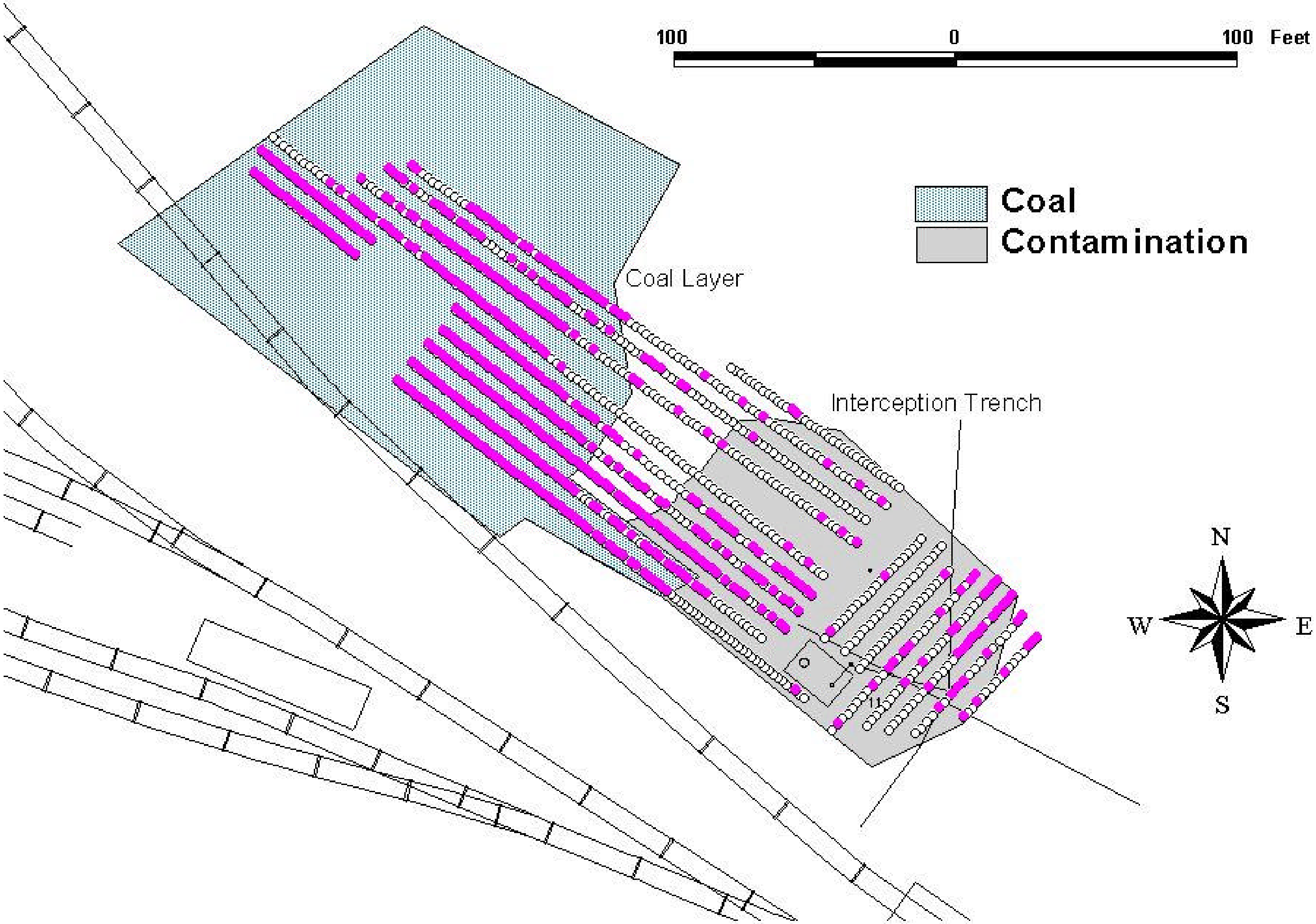


Figure 5.5 - Trees exhibiting below average percent growths (<280%) from March 1997 to November 1999 are colored in magenta

planted, and (3) trees to the east of the interception trench. Reasons for reduced growth in trees within the coal layer, in trees of 2-years when planted, and in tree east of the interception trench will be discussed below.

5.2.1 Comparisons of Heights/Growth between Spatial Areas

Figure 5.6 illustrates that of the 109 trees that have died since November 1999, approximately 70% occurred in the area of no contamination and coal, 17 occurred in the area of contamination and no coal, 8% occurred in the area of contamination and coal, and 5% deaths occurred in the area of no contamination and no coal. The largest percentages of the 109 trees that have died are shown present in the area with no contamination and coal. Thus, the coal layer appears to adversely affect tree growth. These results suggest the impermeable coal layer plays a more significant factor in tree mortality than tree competition or level of contamination.

Figure 5.7 is a plot of circumference versus tree height as of November 1999. A good correlation exists between circumference size and tree height. The taller trees have larger circumferences, which is expected. Points representing large circumferences and tall heights are dominated by areas lacking coal. The areas containing coal do not reach into the upper portion of the graph, which illustrates the reduced growth within the areas of coal. This plot also supports the possibility of analyzing the circumferences in the same manner as heights were analyzed. However, as the tree height increases, greater scatter is exhibited in the data.

Figure 5.8 depicts the average total growth of the trees between measurement periods for different areas. The Figure 5.8a illustrates the growth of trees if the site was divided based on coal and on contamination separately. The trees grouped as No Coal and Contamination display the highest total growth. As time increases, the difference in growth between the No Coal and Contamination growths and the Coal and No Contamination growths becomes more pronounced. Tree growth was plotted (Figure 5.8b) in the four spatial areas previously mentioned (contamination and coal, contamination and no coal, no contamination and coal, no contamination and no coal). The trees grouped in the areas of Contamination/No Coal and No Contamination/No Coal display the highest growth rates. Thus, the coal layer appears to adversely affect tree

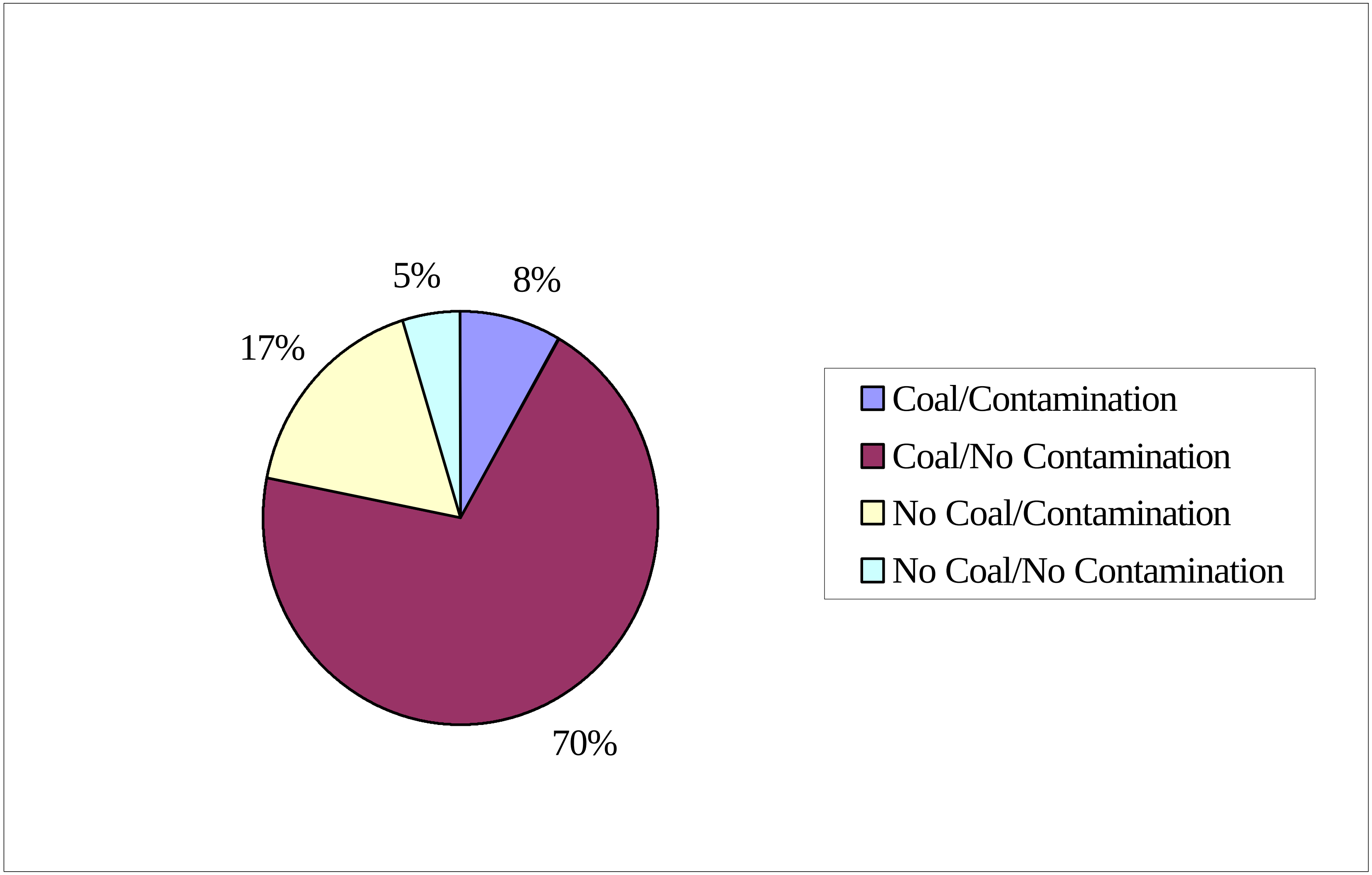


Figure 5.6- Percentage of dead trees within each spatial area (109 total dead trees)

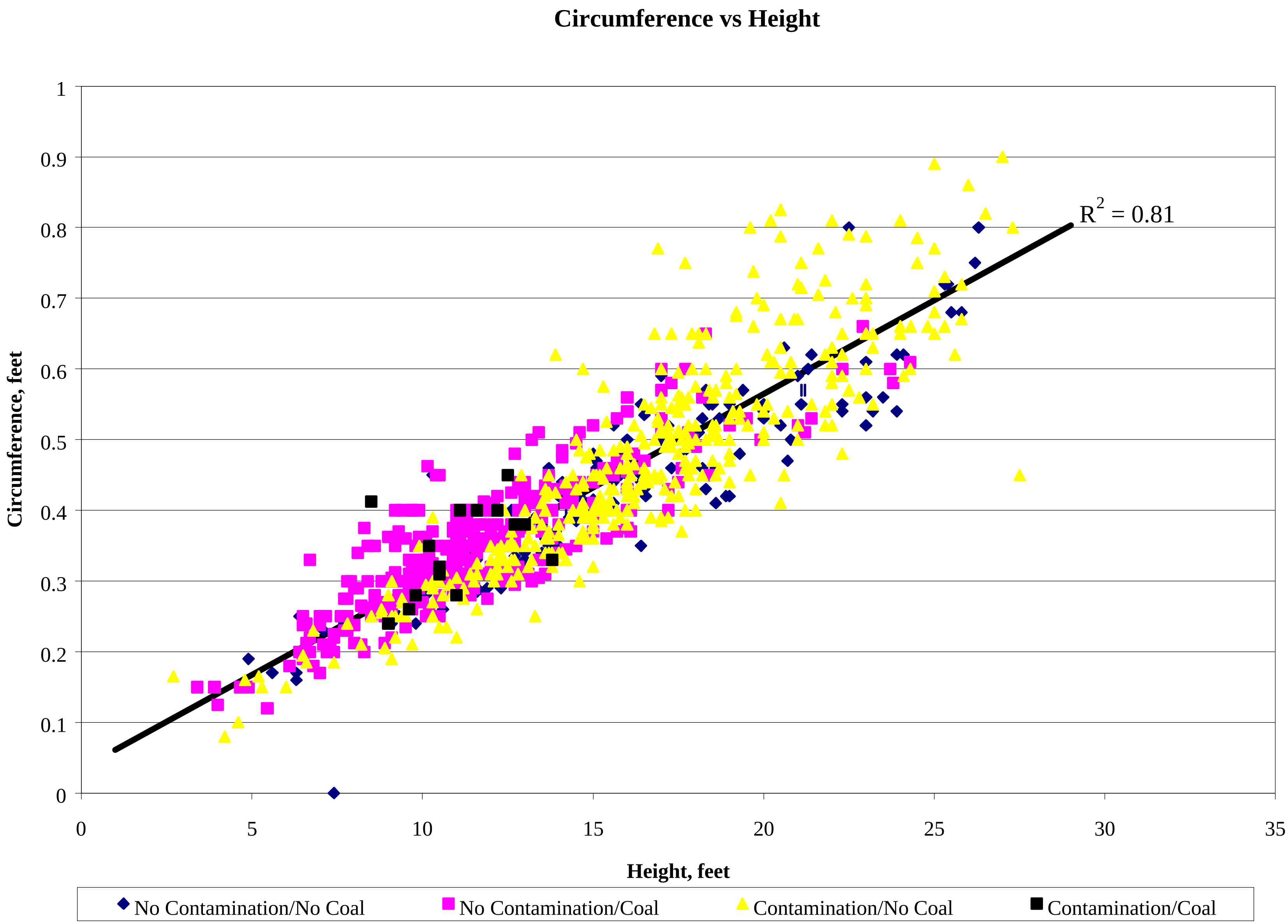


Figure 5.7 - Comparison of height and circumference in November 1999

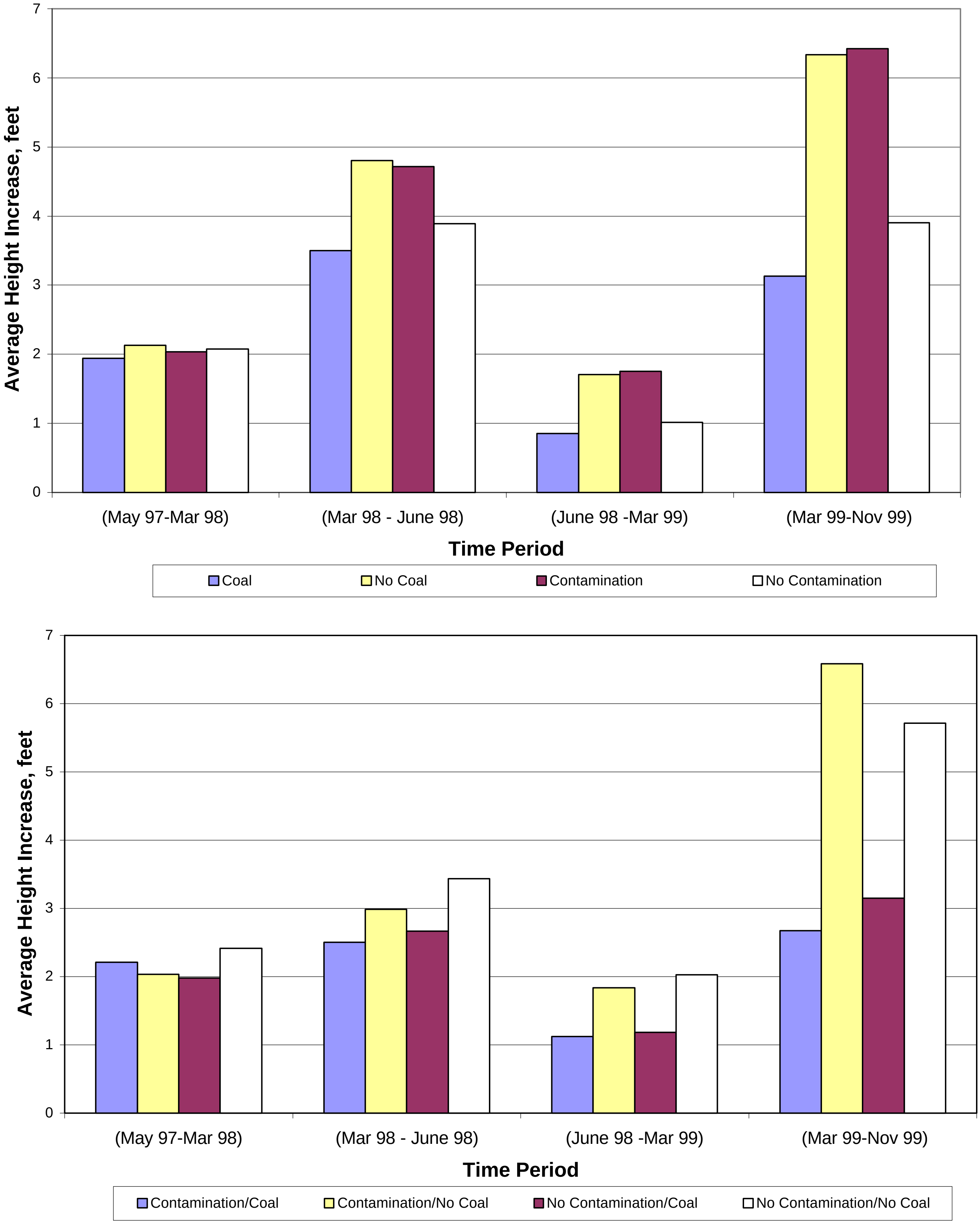


Figure 5.8(a and b): Total change in height vs. time accounting for influences of coal only, contaminationonly, and then accounting for both factors in tree growth.

growth. The first growth period between May 1997 and March 1998 on each plot is most probably affected by the trees becoming established and the assumptions regarding tree height at the beginning of the study. Reduced growths between June 1998 and March 1999 on each plot are most likely a result of drought conditions.

The impermeable nature of the coal layer is similar to a situation in 1990 at a nitrogen-contaminated site in New Jersey (Nyer, 1996). The site could not be pumped efficiently and soil conditions were such that the aquifer could be considered an aquiclude. Thus, the soil conditions were a major impediment to deep root penetration. The coal layer at the Oneida site appears to impact the poplar trees in a similar manner, thereby impeding their growth.

Figure 5.8 also suggests the contaminant does not appear to adversely affect tree growth, which is consistent with lab tests and field tests previously mentioned (Chaineau, 2000; Kilbane 1998; Liste, 1999; Zappi, 1996). Figure 5.9 illustrates the average percent growth of the trees between measurement periods for the same areas presented in Figure 5.8. Percent growth was analyzed to minimize effects of the assumption the 2-years-old trees were six feet tall upon planting. The top graph indicates greater growth in areas of No Coal and in areas of Contamination, which is similar to the results of Figure 5.8. However, the area of Contamination/No Coal displays the highest and most consistent growth pattern of any of the four spatial areas. This suggests that trees in areas of contamination and no coal experienced the most healthy height change and percent growth relative to those measured at the site. In should not be inferred without further research that the contamination is actually benefiting tree growth.

Tree growth between the spatial divisions in the first couple of years is similar. This is expected since the trees needed time to establish themselves. This is consistent with a study done by Licht (1994) in which poplar trees were not considered established until 2 years into the study. Also, early groundwater modeling of the Oneida site indicated limited evapotranspiration in the first two years of study, which would indicate the possibility the trees were not yet affected by site conditions (Loftis, 1999). Another expected trend was the apparent decline in growth outside of the growing season. The measurements between June and December of 1998 illustrate limited growth during late summer through fall and winter months. Dry summer conditions may explain the limited

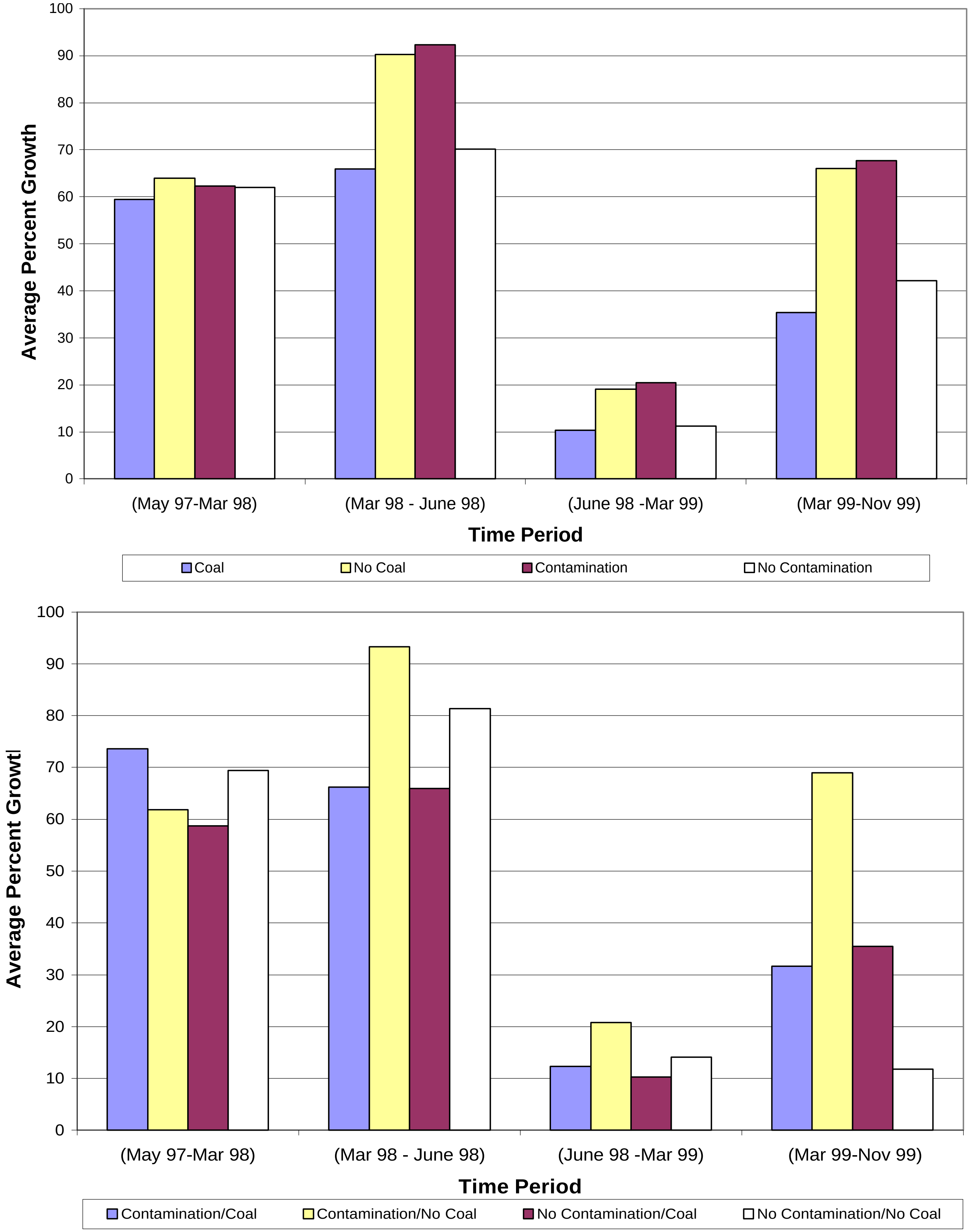


Figure 5.9(a and b): Percent change in height vs. time accounting for influences of coal only, contaminationonly, and then accounting for both factors in tree growth

growth in the months between June and October.

5.2.2 Comparisons of Basal Area between Spatial Areas

The basal area was also calculated as an indicator of tree health. When the basal area is related to tree height, tree stand competition can be evaluated. A natural thinning process has been observed among densely planted trees (DeBell et al., 1997; Schnoor et al., 1995). Evaluating tree stand competition will eliminate speculation that a high mortality rate within a given spatial area is due to tree stand competition within that area, thereby accentuating coal and contamination effects.

Figure 5.10 illustrates the basal area growth of the trees versus the competition index between circumference measurement periods. Each point on the graph represents basal areas and competition indexes at a single point in time (measurement periods of June 1998, December 1998, June 1999, and November 1999). This graph suggests the trees outside the coal exhibit stronger growth patterns when compared to trees inside the coal layer. Another point to notice is the continued rise in basal area growth of poplar trees outside the coal layer as the competition index increases, which indicates a continued increase in growth. The continued growth exhibited by trees not planted over coal indicates a less stressed environment. The basal area growth has already begun to decline between December 1998 and June 1999, indicating a stressed environment. It is hypothesized that the coal layer is preventing root penetration; thus, the trees are being starved of water and nutrients. The tree stand density is the same for each spatial area; thus, the high tree density can be ruled out as the detrimental factor.

5.2.3 Comparisons of Growth Rates of Different Aged Trees

Another analysis included growth rate comparisons of the 1-year-old and 2-year-old trees. It was assumed from the previous results that the coal layer had the greatest impact upon tree growth; thus, for the purpose of this analysis, contaminant variations were not taken into account. Figure 5.11 depicts the growth trends of the 1-year-old and 2-year-old trees inside and outside the coal layer. It appears the 1-year-old trees do exhibit higher growth percentages when compared to the 2-year-old trees. It is surmised that the 1-year old trees have not been impacted as much as the 2-year-old trees due to a

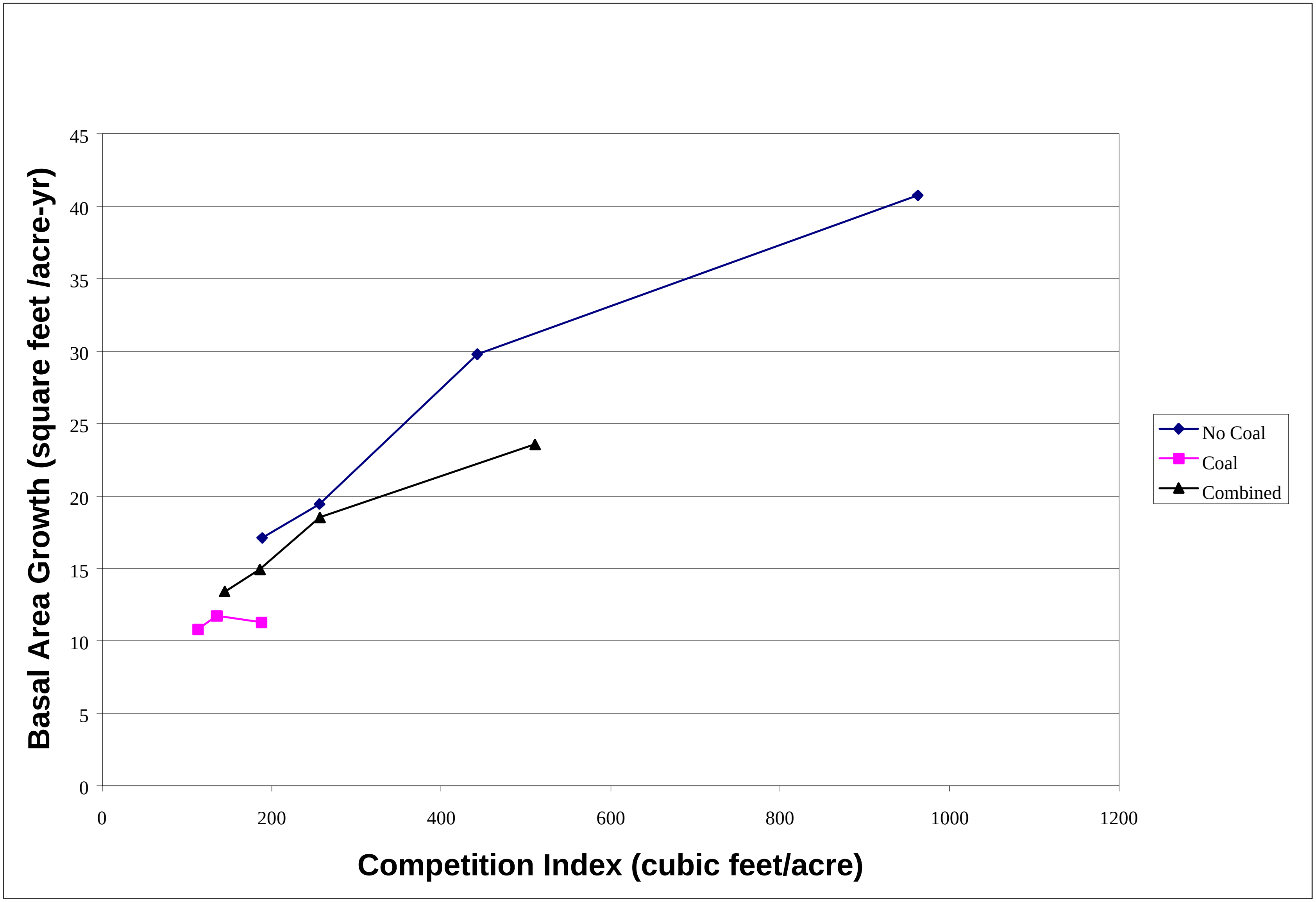


Figure 5.10- Basal area growth versus competition index over time

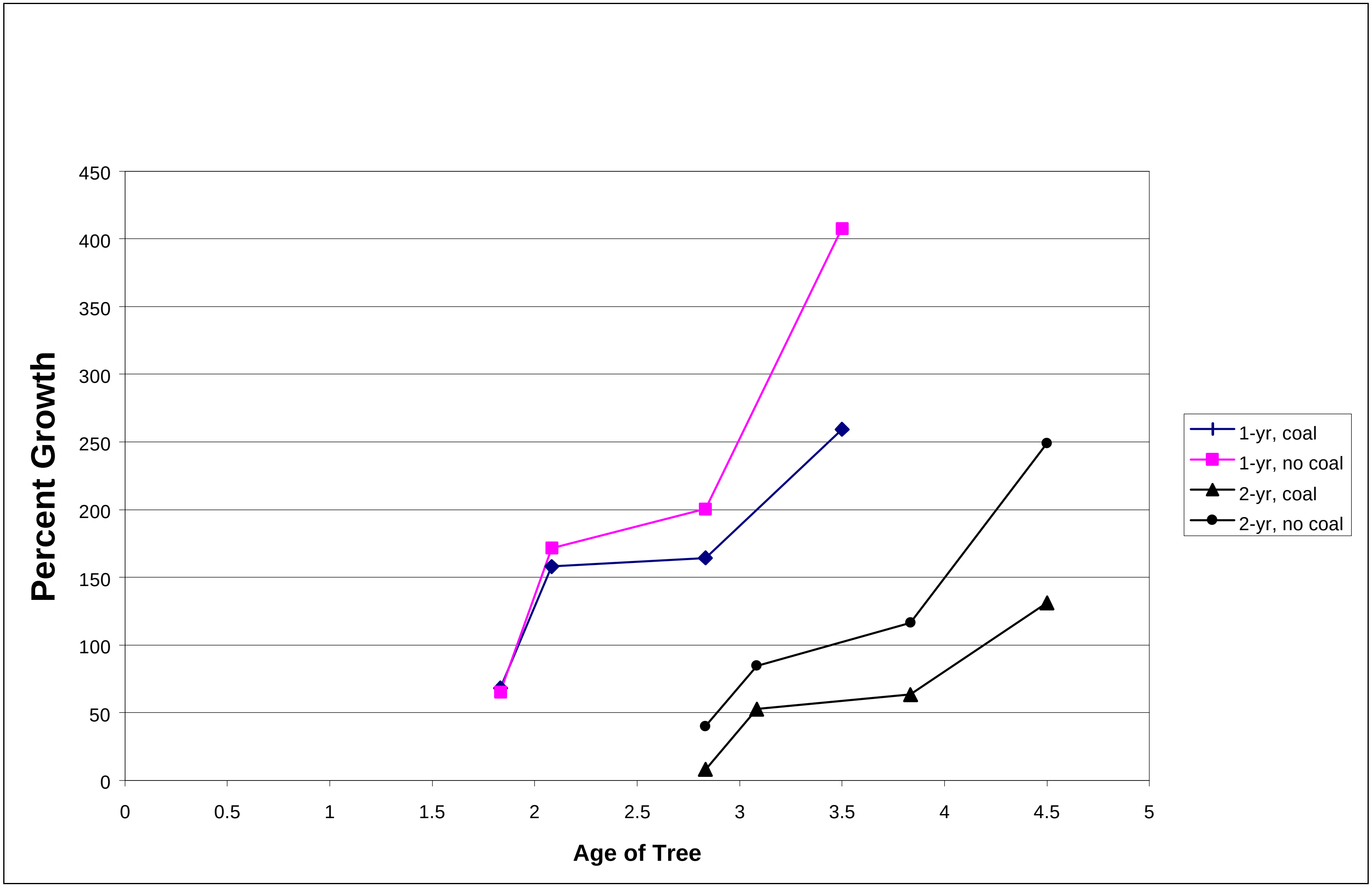


Figure 5.11**-** Percent height change in trees of different planting age over time

shallower root depth. This data also supports studies that indicate faster growth at earlier stages in the life of a tree. The slowed growth rate may become important as time progresses. Chaineau observed a decrease in degradation rates of PAHs as the growth rate of maize decreased. Comparing trees of the same age illustrates a slightly higher growth percentage for those trees outside the coal layer than inside the coal layer, which supports the results from Figures 5.8 and 5.9. The period of lag in growth during the fall and winter months can be seen in all four groups illustrated.

5.2.4 Effects of Interception Trench on Tree Growth

A noticeable decline in tree growth occurs east of the interception trench. Of the 61 trees planted east of the interception trench, 33 of those trees are growing at reduced rates. Because poplar trees are phreatophytes, thus relying on the ground water for their supply of water, the lowering of the ground water table by the interception trench may be starving the trees. Also, gravel backfill used during the construction of the trench may affect root penetration. Further analysis of root zone depth versus ground water levels may aid in determining the role of the groundwater table in tree growth.

5.3 Changes in Contamination Levels and Tree Growth

Figure 5.12 illustrates the position of the selected multi-level samplers in relation to the phytoremediation system and shows the area over of coverage over the entire site. Table 5.1 summarizes the assumed root depths using the “1/3rd rule” extracted from the measured heights in March and November 1999. In March 1999, the average root depth over the selected samplers is 3.1 feet, with a minimum root depth of 1.2 feet and a maximum root depth of 6.5 feet. In November 1999, the average root depth over the selected samplers is 5.3 feet, with a minimum root depth of 1.7 feet and a maximum root depth of 8.7 feet. It indicates the highest growth around ML-20 and the lowest growth around ML-8 and ML-11.

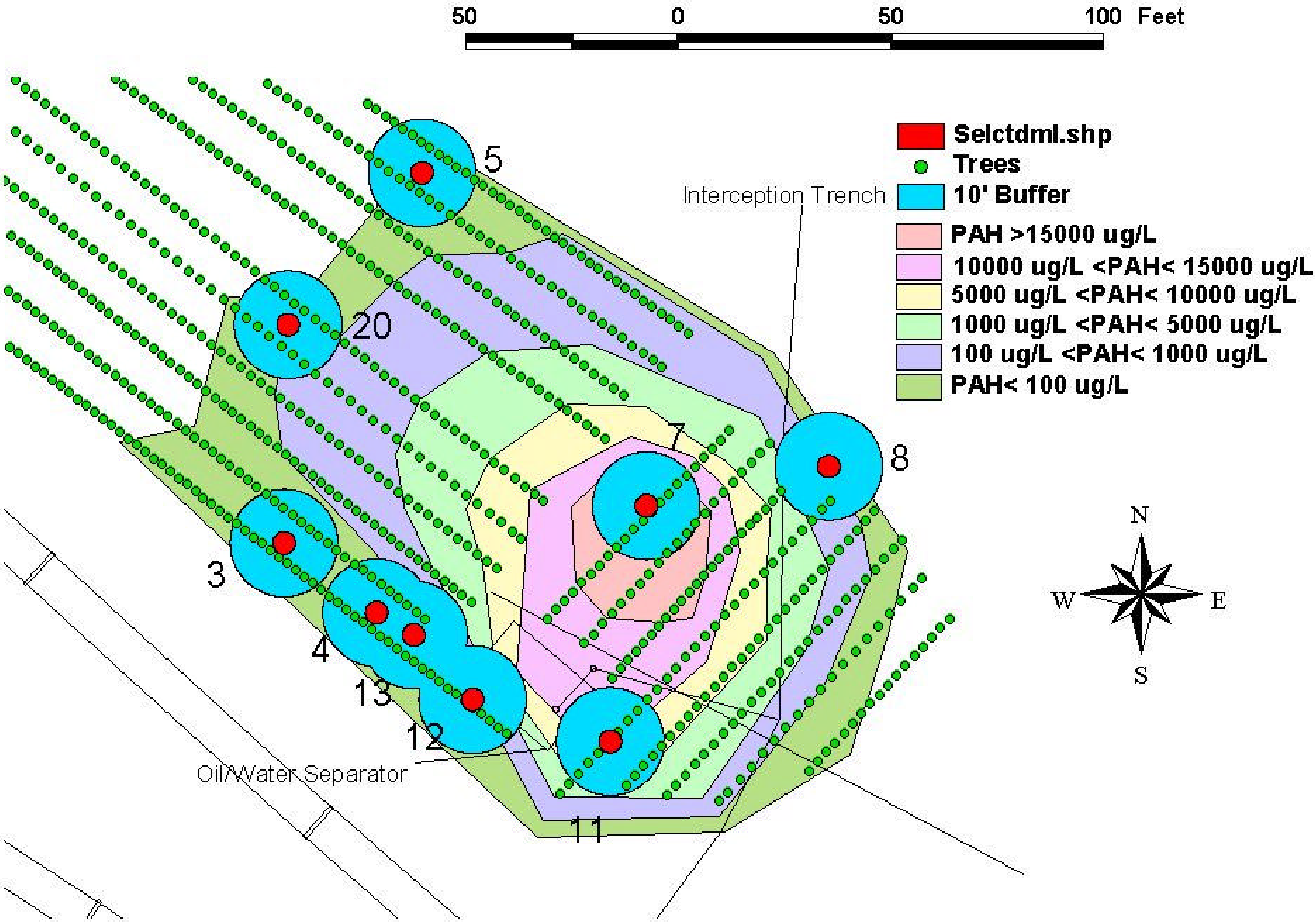


Figure 5.12 - Selected samplers and the 10' radius of influence and spatial distribution of six areas of maximum concentration

Table 5.1- Average and range of tree heights 10' from selected multi-level samplers

Multi-Level Sampler	March 1999				November 1999			
	Measured Height (ft)		Assumed Root Depth (ft)		Measured Height (ft)		Assumed Root Depth (ft)	
ML-3	Average:	7.0	Average:	2.3	Average:	11.0	Average:	3.7
	Minimum:	5.7*	Minimum:	1.9	Minimum:	11.0*	Minimum:	3.7
	Maximum:	11.5	Maximum:	3.8	Maximum:	20.0	Maximum:	6.7
ML-4	Average:	11.1	Average:	3.7	Average:	19.0	Average:	6.3
	Minimum:	8.5	Minimum:	2.8	Minimum:	15.0	Minimum:	5.0
	Maximum:	13.3	Maximum:	4.4	Maximum:	23.0	Maximum:	7.7
ML-5	Average:	8.5	Average:	2.8	Average:	14.0	Average:	4.7
	Minimum:	4.9	Minimum:	1.6	Minimum:	5.0	Minimum:	1.7
	Maximum:	11.0	Maximum:	3.7	Maximum:	18.0	Maximum:	6.0
ML-7	Average:	9.0	Average:	3.0	Average:	17.0	Average:	5.7
	Minimum:	3.7	Minimum:	1.2	Minimum:	5.0	Minimum:	1.7
	Maximum:	11.1	Maximum:	3.7	Maximum:	20.0	Maximum:	6.7
ML-8	Average:	7.0	Average:	2.3	Average:	11.5	Average:	3.8
	Minimum:	6.2	Minimum:	2.1	Minimum:	9.0*	Minimum:	3.0
	Maximum:	8.3	Maximum:	2.8	Maximum:	14.0	Maximum:	4.7
ML-11	Average:	7.3	Average:	2.4	Average:	14.0	Average:	4.7
	Minimum:	5.5	Minimum:	1.8	Minimum:	10.0	Minimum:	3.3
	Maximum:	8.7	Maximum:	2.9	Maximum:	16.0	Maximum:	5.3
ML-12	Average:	10.5	Average:	3.5	Average:	16.0	Average:	5.3
	Minimum:	8.8	Minimum:	2.9	Minimum:	10.0	Minimum:	3.3
	Maximum:	12.0	Maximum:	4.0	Maximum:	21.0	Maximum:	7.0
ML-13	Average:	11.1	Average:	3.7	Average:	19.0	Average:	6.3
	Minimum:	8.5	Minimum:	2.8	Minimum:	13.0	Minimum:	4.3
	Maximum:	13.0	Maximum:	4.3	Maximum:	23.0	Maximum:	7.7
ML-20	Average:	13.6	Average:	4.5	Average:	21.0	Average:	7.0
	Minimum:	8.4	Minimum:	2.8	Minimum:	16.0	Minimum:	5.3
	Maximum:	19.5	Maximum:	6.5	Maximum:	26.0	Maximum:	8.7

* Indicates presence of tree(s) that had died were present in area of sampler

Table 5.2 summarizes the change in concentrations with respect to elevation and time at each multi-level sampler. Multi-level sampler 5 was omitted because no PAH concentrations have ever been detected. The largest decreases in concentration (>3700 µg/L) occurred at ML-3, ML-4, ML-7, and ML-8. Concentrations in the upper ports of every sampler have decreased. Increases in concentration ranging from 10 µg/L to 11000 µg/L have occurred at ML-7, ML-8, ML-11, and ML-13. All the increases take place in

Table 5.2 - Total PAH concentrations at sampling depths for selected multi-level samplers at specified sampling times

Sampler ID	Ground Elevation (ft above MSL)	Elevation (ft)	March-98 (ppb)	June-98 (ppb)	Jan-99 (ppb)	June-99 (ppb)	July-99 (ppb)	Dec-99 (ppb)	Approximate ΔC since March 1998 (ppb)
ML-3	1433.61	1428.30		114.0	0.0				-114.0
ML-3		1427.30	413.8	11.1	0.0		0.0	0.0	-413.8
ML-3		1426.30		141.4	8.7		0.0	0.0	-141.4
ML-3		1425.30	2375.0	91.2	0.0		0.0	0.0	-2375.0
ML-3		1424.30		1623.7	1078.5	1300.0	158.5	34.3	-1589.4
ML-3		1423.30	3874.5	1391.4	959.3	3530.5	120.2	141.6	-3732.9
ML-3		1422.30		1950.0	1491.9	1650.4		1010.3	-939.7
ML-4	1433.83	1427.14		1043.5	0.0				-1043.5
ML-4		1426.14	75.2	474.4	13.4		0.0	0.0	-75.2
ML-4		1425.14		1952.5	604.8	939.8	135.6	4.6	-1947.9
ML-4		1424.14	1396.3	738.4	1235.4	877.7	747.1	416.6	-979.7
ML-4		1423.14	3877.6	132.6	607.2	261.3	328.3	130.8	-3746.8
ML-4		1422.14	942.0	200.8		124.6	363.1	482.8	-459.2
ML-7	1432.46	1425.21	9180.0	26.7	6825.7				-9180
ML-7		1424.21	13471.8	13405.2	13912.7		10418.2	903.7	-12568.1
ML-7		1423.21	41.3	14890.5	18525.2	16203.6	17761.6	11050.9	+11009.6
ML-7		1422.21	12309.5	14461.3	15657.8	12314.2	16939.6	0.0	-12309.5
ML-8	1430.86	1423.59	5737.5		0.0			0.0	-5737.5
ML-8		1422.59	5458.0		20.6	0.0	28.2	0.0	-5458.0
ML-8		1421.59	3979.6		593.3	19.1	62.8	766.8	-3212.8
ML-8		1420.59	4254.4		2542.3	1037.2	4.1	1150.7	-3103.7
ML-8		1419.59	1049.5		37.0	31.3	4.1	0.0	-1049.5
ML-8		1418.59	110.5		260.7		9.9	120.8	+10.3

Sampler ID	**Ground Elevation (ft above MSL)**	**Elevation (ft)**	**March-98 (ppb)**	**June-98 (ppb)**	**Jan-99 (ppb)**	**June-99 (ppb)**	**July-99 (ppb)**	**Dec-99 (ppb)**	**Approximate ΔC since March 1998 (ppb)**
ML-11	1432.64	1422.61	114.0		113.3		130.5	86.5	-27.5
ML-11		1421.61	4014.1		10436.1	4458.7	428.2	433.1	-3581
ML-11		1420.61			3062.0	1594.1	1756.8	1253.1	-1809
ML-11		1419.61					47437.4	0.0	-47437.4
ML-11		1418.61	4214.4			5884.0			+1670
ML-12	1432.91	1424.81		314.5	43.0		142.2		-172.3
ML-12		1423.81		771.7	125.8		309.8	68.0	-703.7
ML-12		1422.81	570.5	1079.3	140.5	0.0	183.1	65.9	-504.6
ML-12		1421.81	2412.2	4299.7	694.7	0.0	95.7	176.5	-2235.7
ML-12		1420.81			3711.0	1245.2	1247.1	2102.2	-1608.8
ML-13	1433.52	1425.46		317.6	42.5				-275.1
ML-13		1424.46			785.5				NA
ML-13		1423.46		540.0	453.7		639.9	450.6	-89.4
ML-13		1422.46		538.2	174.0	1315.1	1910.2	266.7	-271.5
ML-13		1421.46				243.9	58.5	189.5	-54.4
ML-13		1419.46				43.7	119.7	139.8	+96.1
ML-20	1433.5	1425.21			34.4		0.0		-34.4
ML-20		1424.21			56.8		0.0		-56.8
ML-20		1423.21				0.0	0.0		0.0
ML-20		1422.21					0.0		NA

the lower two ports of the samplers. Trends in each sampler selected for analysis will be discussed below.

PAH concentrations at ML-3 have decreased throughout almost the entire sampling period. The maximum root depth calculated around ML-3 was 3.8 feet below land surface (1429. 81 feet above MSL) during March 1999 and 6.7 feet below land surface (1426. 91 feet above MSL) during November 1999. It appears the roots are progressing downward through the contamination despite higher contaminant concentrations, particularly at the lower ports of the sampler. Even the lower ports are showing degradation despite the roots not having penetrated the contamination at that depth. The large decrease in concentration between June and July 1999 occurs during the peak growing season. The decrease in contaminant levels could be the result of the plume moving past the sampler, degradation by microbes in the rhizosphere, sorption by roots, or some combination.

A constant decrease in PAH levels has occurred in the upper sampling ports at ML-4, which lies at the trailing edge of the plume, while lower ports peak around January 1999 and then begin a steady decline. The maximum root depth calculated around ML-4 was 4.4 feet below land surface (1429. 43 feet above MSL) during March 1999 and 7.7 feet below land surface (1426. 13 feet above MSL) during November 1999. Figure 5.13 illustrates the concentration versus depth and root zone depth (based on average tree height) over time at ML-4. From this figure, it appears the roots have penetrated the area of contamination and the water table. Maximum root depths were not included on the figures because they differ only 1 to 2 feet from the average. Figure 5.14 illustrates the dissolved oxygen concentration versus depth and root zone depth (based on average tree height) over time at ML-4. The root depth of the trees suggests definite contact between the roots and the PAHs. The decrease in contaminant levels could be the result of the plume moving past the sampler or tree uptake.

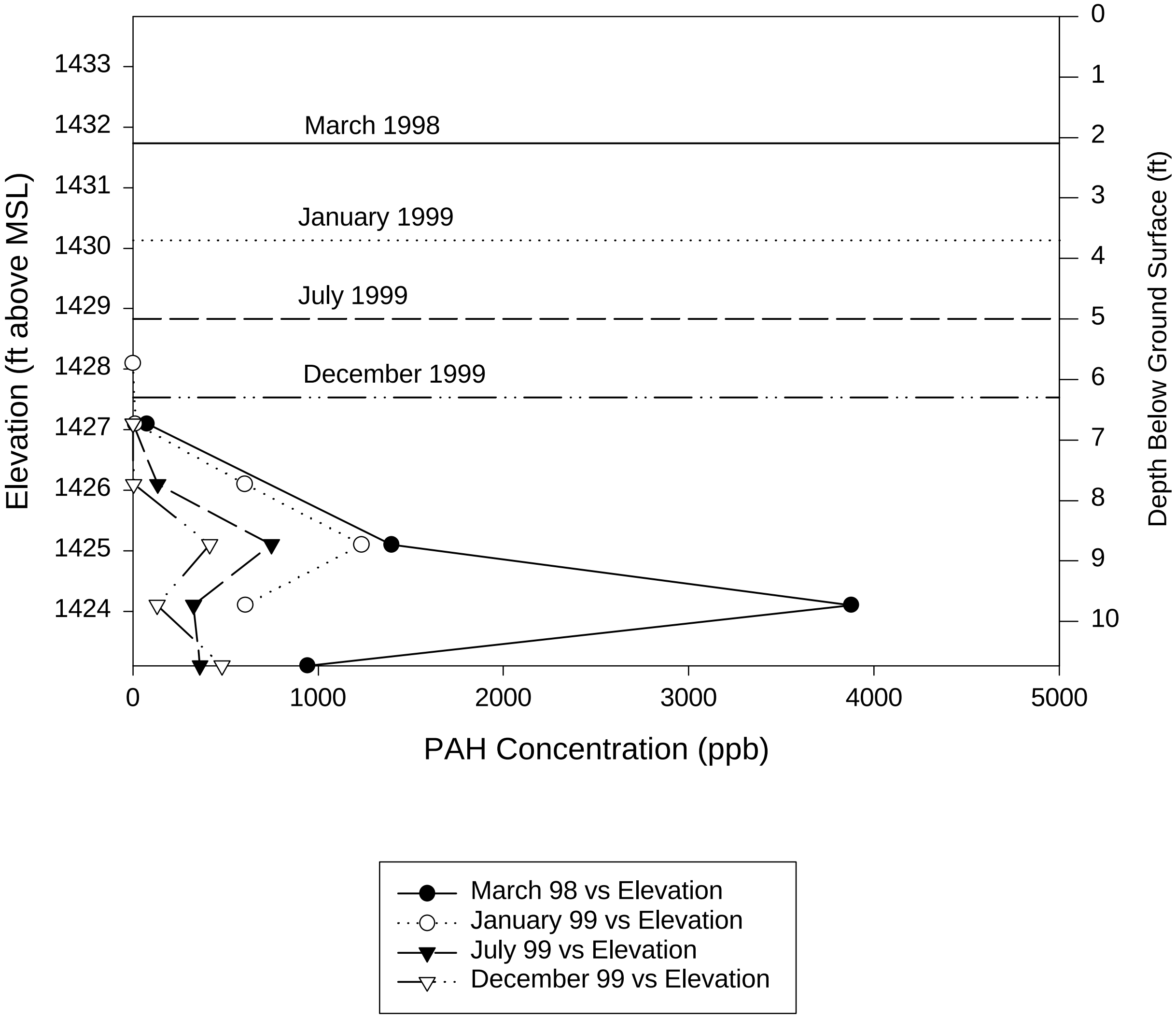


Figure 5.13: Contamination versus depth and root zone depth (based on average tree height) between March 1998 and December 1999 around ML-4.

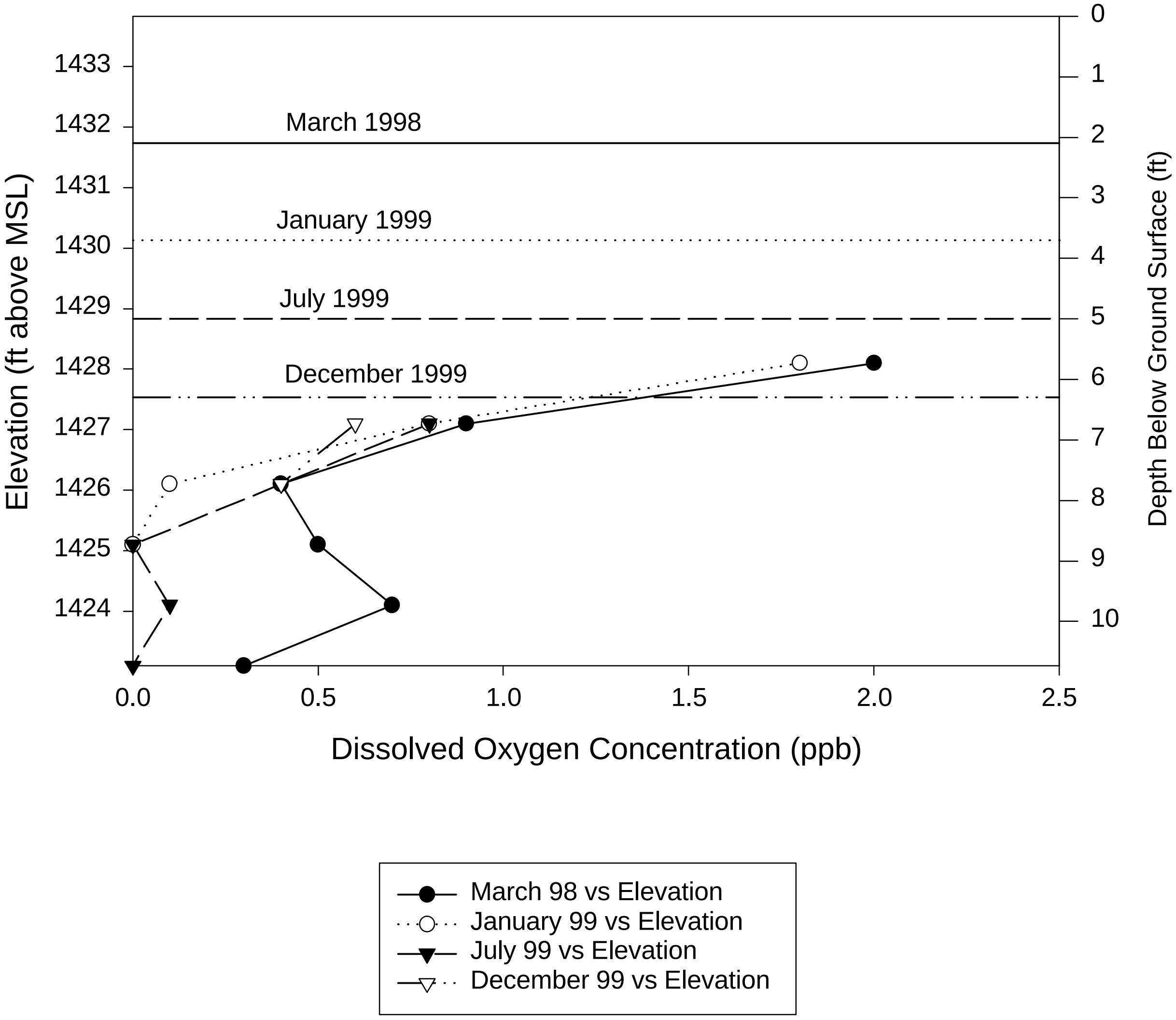


Figure 5.14: Dissolved oxygen versus depth and root zone depth (based on average tree height) between March 1998 and December 1999 around ML-4.

PAH concentrations peak in January 1999 and then a steadily decline at ML-7. The maximum root depth calculated around ML-7 was 3.7 feet below land surface (1428. 76 feet above MSL) during March 1999 and 6.7 feet below land surface (1425. 76 feet above MSL) during November 1999. No PAH concentrations have been detected in the upper portion of the sampler. Figure 5.15 illustrates the concentration versus depth and root zone depth (based on average tree height) over time at ML-7. Maximum root depths were not included on the figures for the same reason they were omitted from the ML-4 analysis. Dissolved oxygen was not plotted over time since it was never detected in the sampler. The roots are shown to not have penetrated contaminated soil or the water table as of November 1999. Thus, microbes may be assumed responsible for contaminant degradation after January 1999.

PAH concentrations at ML-8 have also decreased throughout almost the entire sampling period. The maximum root depth calculated around ML-8 was 2.8 feet below land surface (1428.06 feet above MSL) during March 1999 and 4.7 feet below land surface (1426. 16 feet above MSL) during November 1999. The roots have yet to penetrate contaminant levels in ML-8, but are within a foot of the contamination. The upper sampling ports show little to none PAH contamination. However, the interception trench installed in May 1992 should capture contaminants before they reach ML-8. Limited groundwater availability due to the low groundwater table at ML-8 could stunt tree growth; thereby making root penetration to groundwater difficult.

PAH concentrations in ML-11, ML-12, and ML-13 seem to fluctuate between sampling periods. The maximum root depth calculated around ML-11 was 2.9 feet below land surface (1429.74 feet above MSL) during March 1999 and 5.3 feet below land surface (1427. 34 feet above MSL) during November 1999; the maximum root depth calculated around ML-12 was 4.0 feet below land surface (1428.91 feet above MSL) during March 1999 and 7.0 feet below land surface (1425. 91 feet above MSL) during November 1999; and the maximum root depth calculated around ML-13 was 4.3 feet below land surface (1429. 22 feet above MSL) during March 1999 and 7.7 feet below land surface (1425. 82 feet above MSL) during November 1999. It appears the roots have yet to penetrate contaminant levels in ML-11 or ML-12 but have managed to penetrate the contamination at ML-13. ML-13 does show some decrease in PAH concentrations

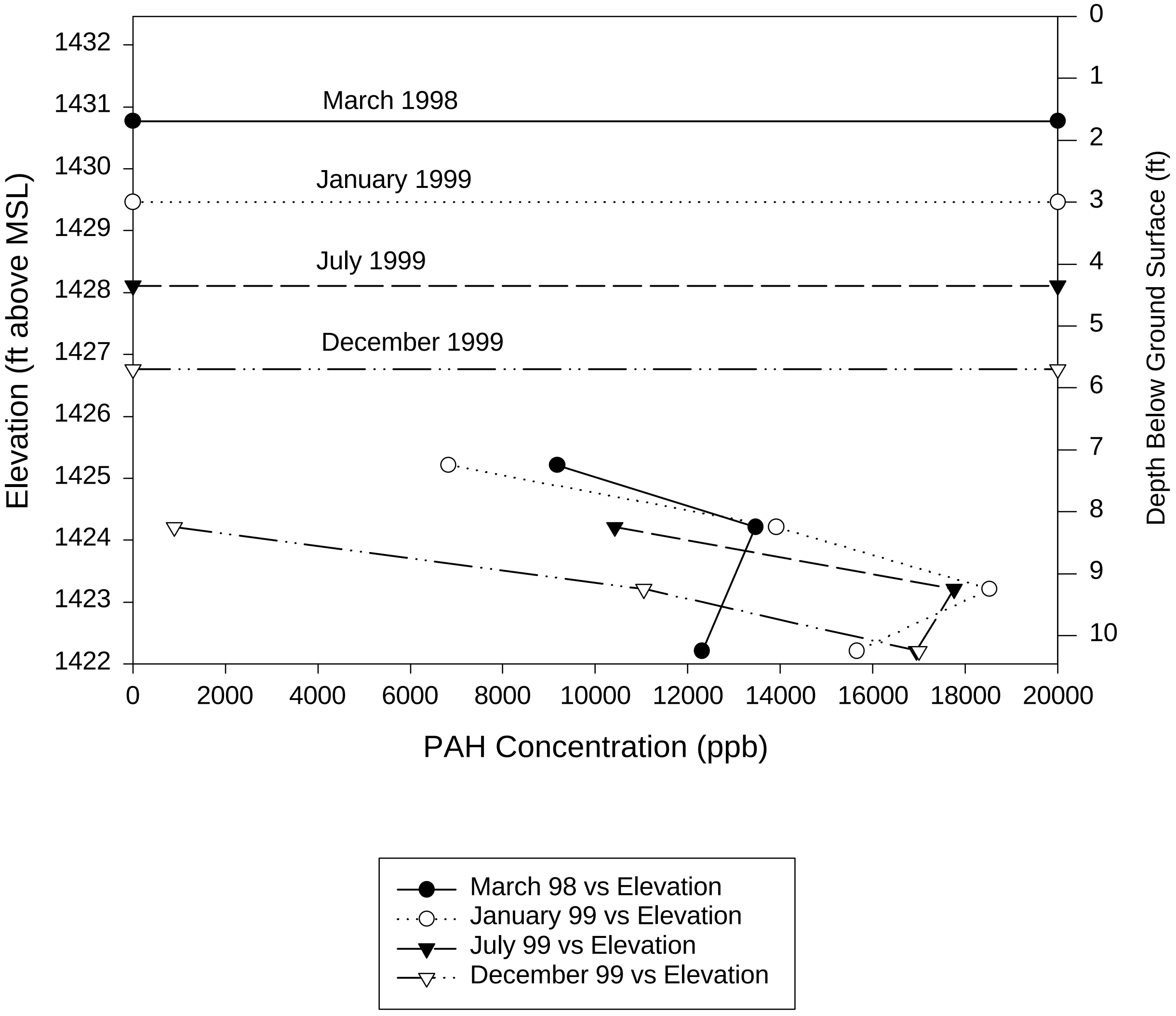


Figure 5.15: Contamination versus depth and root zone (based on average height) between March 1998 and December 1999 around ML-7.

in the upper port, and like ML-11 and ML-12, shows some fluctuations in the lower ports. A trend in the PAH data is hard to determine for any of these samplers due to the fluctuation in contaminant levels.

A decrease in PAH concentrations has been observed at ML-20 since the first PAH concentrations were detected in January 1999. The maximum root depth calculated around ML-20 was 6.5 feet below land surface (1427 feet above MSL) during March 1999 and 8.7 feet below land surface (1424. 8 feet above MSL). The tree roots have apparently penetrated what would have been the contaminant surface in November 1999. No contamination was detected since January 1999, at which time the roots do not appear to have reached the contamination.

The trend of decreasing PAH concentrations in the upper sampling ports of almost every sampler indicates PAH degradation. Assuming root penetration of 1/3rd-height indicates some roots have the opportunity to uptake PAH contamination. Of the multi-level samplers chosen for analysis, it is interesting to note those samplers who have experienced definite steady decreases in PAH levels (ML-3, ML-4, and ML-7) are surrounded by trees whose roots have either penetrated or are directly above the contamination. Degradation within a couple of feet of assumed root penetration indicates positive effects just below the root zone. Further research to accurately delineate the root zone is recommended.

5.4 Division of Trees Based on Maximum PAH Concentrations

No adverse impact on tree growth appeared in the areas of contamination when compared to the areas of coal. Thus, impacts of varying total PAH concentrations on the trees were investigated. Plume interpolation performed in Surfer and based on the maximum concentration at a single port led to the division of the contamination into six areas centered around ML-7. Figure 5.12 illustrates the areas into which the trees were divided. Each color represents a different area as shown on the plot. The concentration of each area is given strictly for comparison purposes and is not considered exact. Table 5.3 summarizes the six areas of maximum concentration into which the plume was divided. Approximately 60% of the trees planted over contamination lie over concentrations of 1000 ppb or less. The change in tree height for each area was then compared.

Table 5.3 - Spatial division of contamination based on maximum concentrations at a single port.

Designation	Maximum Concentration Level (single port) ppb	Number of Trees
Area 1	> 15000	29
Area 2	10000 - 15000	37
Area 3	5000 - 10000	45
Area 4	1000 - 5000	79
Area 5	100-1000	132
Area 6	<100	134

Figure 5.16 illustrates the average change in height of the trees within the area of the plume between measurement periods. No significant difference is apparent from Figure 5.16, which would indicate higher contaminant levels do not have a greater impact on tree height. It is difficult to delineate which trees are affected by each value of contamination, especially since interpolation is being used. It can be reasonably argued the average contaminant concentration is a more appropriate method for determining impacts of varying concentration levels since maximum concentrations are most likely to occur at the lower sampling ports still out of reach of tree roots. While the table displays maximum concentrations, it may be assumed that similar average concentrations would fall within the same boundaries as maximum concentrations.

5.5 Comparisons to Similar Popular Tree Growth Studies

A study performed by DeBell et al.(1997) on four plots of different species of poplar tree can be used as a comparison to the trees used in Oneida. The trees in each plot were planted 1.0 meter apart, similar spacing to that of the Oneida study site, and were observed for eight years, while Oneida has been observed for 3 years. All four species of poplars in the study observed an annual decline in growth due to an increase in inter-tree competition. All four clones also experienced the largest total and largest percent growth during the first three years of the eight year study. The average heights of three species of clones remained similar through the first three years, between 8.5 and 9.5 meters (27.9 and 31.2 feet), while the average height of the fourth clone was less throughout the study. Borer damage, a severe windstorm, and competition-related mortality resulted in basal area increases for just two of the four clones.

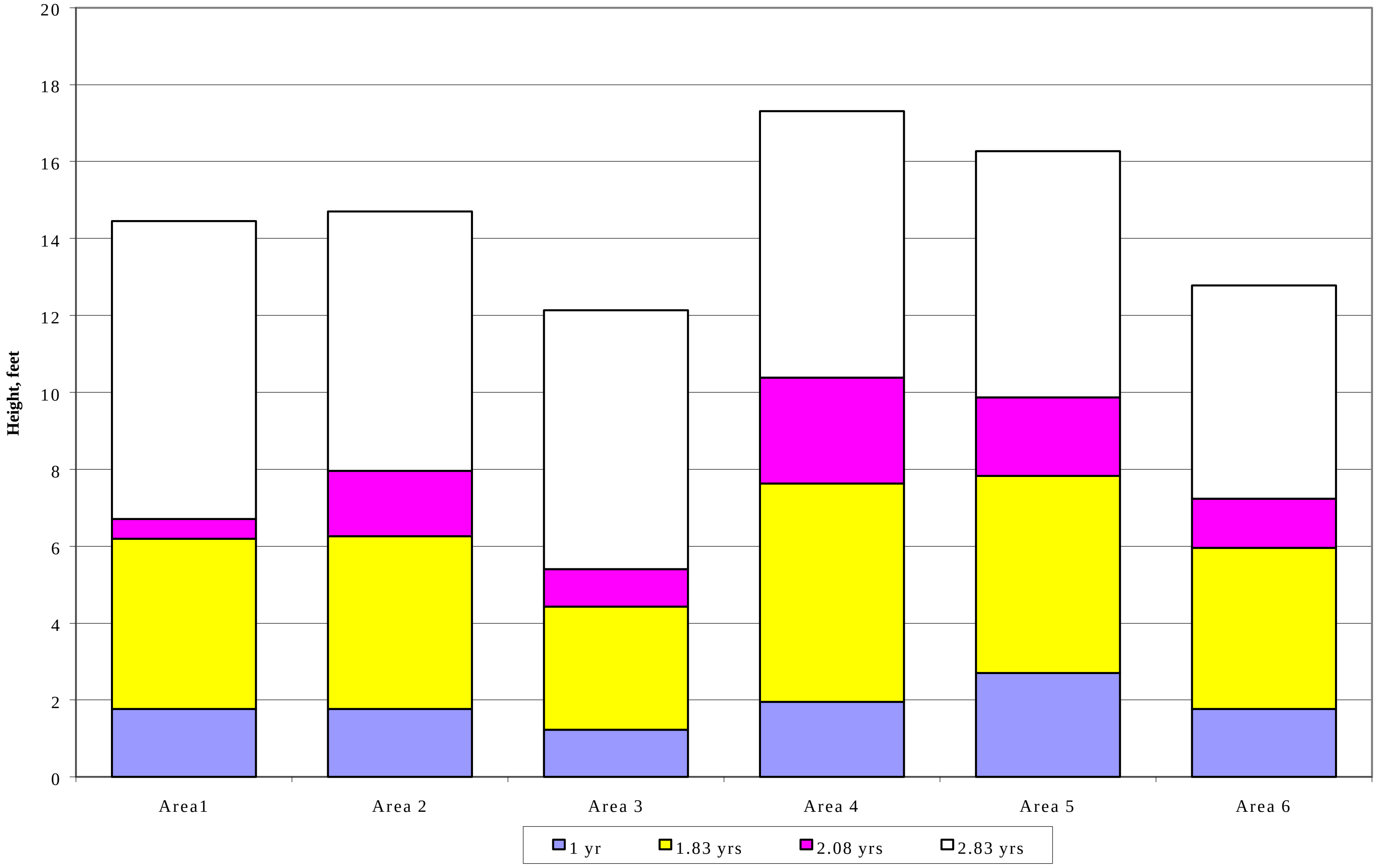


Figure 5.16 – Tree Growth Comparisons among varying contaminated Areas (contamination levels decrease from Area 1 to Area 6)

The competition in the Washington study 1.0-meter (3.28 feet) spaced plantings resulted in “substantial” declines in height and diameter growth by the fourth growing season. Climate conditions differ from Tennessee to Washington, and the Oneida poplar trees have not experienced significant insect damage. It may be surmised tree mortality in Oneida may be due to three factors: coal, contamination, and/or competition. The Oneida trees are similarly spaced to the trees presented in this study and have been sustained for 3 years on the site. Tree competition was shown in Section 5.4 as not being a large problem.

While the aforementioned study included trees not subjected to contamination, it is also interesting to compare height and growth patterns of the Oneida trees with trees in previous studies involving contamination. In a study by Erickson (1994), poplar trees grew well with average heights being 2.07 meters (6.79 feet) in the first year, 3.86 meters (12.66) in the second year, and 6.17 meters (20.24 feet) in the third year. During the second growing season, the trees were able to transpire water from the soil covers at a rate greater than the precipitation (Erickson, 1994). A study done by Hinckley (1993) involved a four- year- old stand of hybrid poplars during midsummer 1992, study trees ranged in height from 11 to 15.1 meters (36.08 to 49.53 feet) and in diameter from 8.3 to 15.1 cm (0.27 to 0.50 feet) (Hinckley, 1993).

Schnoor et al. (1995) reported poplar trees that were known to average 2 meters (6.56 feet) of growth in the first growing season and reach 5-8 meters (16.4 to 26.24 feet) after three years. The study used a tree density of 10,000 trees per hectare (4047 trees per acre), but a natural thinning process decreased the density to about 2000 trees per hectare (809 trees per acre).

Table 5.4 summarizes the growth of poplar trees measured each year of the study. November 1999 was included to illustrate the poplars’ further growth. As shown in Table 5.4, the Oneida poplar trees experienced significantly less growth than reported by Erickson or Schnoor. The poplar trees experienced an average growth of 0.6 meters (2 feet) of growth in the first growing season, 1.22 meters (4 feet) in the second, and approximately 1.68 meters (5.5 feet) in the third growing season. While the average heights reported by Schnoor are closer, they are still measurably larger than the Oneida trees. If the trees inside and outside are average separately, the difference in growth does appear to increase for the trees outside the coal layer, but heights are still measurably smaller than those reported by other studies.

Table 5.4 - Average Tree Height by Growing Season

	March 1997	March 1998	March 1999	November 1999
Average Height across entire site (m)	1.13	1.68	2.80	4.39
Average Height in Coal (m)	1.19	1.68	2.59	3.54
Average Height Outside Coal (m)	1.11	1.71	3.00	4.97

The question arises as to whether or not the decrease in concentrations during the winter months is due to dilution by precipitation, sorption by root system, or natural biodegradation. Groundwater data and water budget analysis suggests similar transpiration rates even when water levels drop below the root zone (Panhorst, 2000). And studies have observed that contaminant uptake on a mass basis is directly proportional to plant transpiration rates when all other factors are constant (Burken, 1996). These results suggest tree uptake in the form of root sorption and biodegradation in the rhizosphere could be occurring outside the growing season.

6.0 Conclusions and Recommendations

The following conclusions may be drawn from the Oneida tree study.

- Reduced tree growth was identified in three specific areas: tree within the coal layer, trees of 2-years when planted, and trees east of the interception trench.
- Although PAH does not appear to adversely affect tree growth, physical site characteristics that limited tree access to water, i.e. coal and interception trench, appear to impede tree growth. However, the coal layer had a greater negative impact on tree growth relative to the interception trench.
- Tree heights in areas of contamination and no coal experienced the most healthy height change and percent growth relative to date. This does not indicate the contamination is facilitating tree growth, but no adverse impacts upon the trees from the contamination appear.
- A comparison of basal areas indicates a stressed environment for the poplar trees inside the coal layer.
- The younger trees experienced higher percent growths than the older trees. This could indicate the potential for higher degradation during early tree life once the trees have become established, which Chaineau (2000) observed with maize in a hydroponic environment.
- The noticeable reduction in tree growth that occurs east of the interception trench is most likely due to limited access to ground water resulting from the lowered ground water table.
- PAH concentrations in the upper ports of multi-level samplers at which the root zone depth has penetrated or close to penetrating have declined. Those multi-level samplers surrounded at which the root zone is greater than a foot from the contamination have not experienced consistent declines in contamination.
- Though the poplar trees have experienced less growth than that of other studies, the limited vertical extent of the aquifer could restrict the depth of root penetration and may affect tree growth.

The following recommendations for this study and similar studies include:

- The data in this study does not indicate the specific mechanism (sorption, plant enzymes, or microbial activity) by which the poplar trees facilitate degradation or stabilization of PAHs. However, more intense data collection would enhance the analysis capabilities of correlating tree growth with changes in concentration. Further research may answer by what processes phytoremediation is effective and to what limits phytoremediation may be used.
- Future analysis of a phytoremediation system must incorporate the advantages of the spatial tools provided by ArcView and AutoCAD Map and groundwater modeling programs designed to illustrate contaminant plumes and their movements, such as GMS and MODFLOW.

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