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Stimulation of Hybrid Poplar Growth in Petroleum Contaminated Soils through Oxygen Addition and Soil Nutrient Amendments

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ABSTRACT

Hybrid poplar trees (*Populus deltoides* × *nigra* DN34) were grown in a greenhouse using hydrocarbon-contaminated soil from a phytoremediation demonstration site in Heath, Ohio. Two independent experiments investigated the effect of nutrient addition on poplar growth and the importance of oxygen addition to root development and plant growth. Biomass measurements, poplar height, and leaf color were used as indicators of plant health in the selection of a 10/5/5 NPK fertilizer applied at 1121 kg/ha (112 kg-N, 24.4 kg-P, 46.5 kg-K per ha) to enhance hybrid poplar growth at the Heath site. Five passive methods of oxygen delivery were examined, including aeration tubes, gravel addition, and an Oxygen Release Compound® (ORC). When ORC was placed in coffee filters above hydrocarbon-contaminated soil, a statistically significant increase of 145% was observed in poplar biomass growth, relative to unamended controls. The ORC in filters also stimulated significant increases in root density. A 15.2-cm interval of soil directly below ORC addition exhibited an increase from 2.6 ± 1.0 mg/cm^3 to 4.8 ± 1.0 mg/cm^3, showing stimulation of root growth in hydrocarbon-stained soil. The positive response of hybrid poplars to oxygen amendments suggests that overcoming oxygen limitation to plants should be considered in phytoremediation projects when soil contamination exerts a high biochemical oxygen demand, such as in former refinery sites.

KEY WORDS: phytoremediation, oxygen addition, total petroleum hydrocarbons (TPH), root density.

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I. INTRODUCTION

The importance of oxygen in the biological remediation of petroleum contamination is well documented, and several methods have been developed to enhance microbial biodegradation of hydrocarbons by delivering molecular oxygen. These include bioventing and *in situ* air sparging, which are based on forced transport of oxygen to the subsurface (Norris *et al*., 1994; Weidemeier *et al*., 1999). However, the importance of enhancing soil aeration for the growth of plants in phytoremediation of hydrocarbon-contaminated soils has not been previously addressed.

Advocates of phytoremediation suggest that plants enhance the oxygenation of contaminated soils through two mechanisms. First, specially adapted plants use aerenchyma, channels of reduced air resistance, to transport oxygen to the root zone, enhancing aerobic biological degradation (Erickson *et al*., 1994; Shimp *et al*., 1993), **although there are no reports of aerenchyma within hybrid poplars, the subject of this report (??)**. Second, soil dewatering and fracturing increases soil porosity, allowing increased diffusion of atmospheric oxygen (Schnoor *et al*., 1995). Yet, root turnover and root exudation provide microbial populations with simple carbon sources that could deplete soil oxygen when metabolized (Lynch, 1990). Thus, it is unclear if plants commonly used in phytoremediation (e.g., hybrid poplar trees) are net sources or sinks of oxygen in contaminated soil (Lee *et al*., 2000). Furthermore, plant roots are known to require oxygen (Neuman *et al*., 1996). The root density of plants used in phytoremediation, however, has not been characterized in soils with reduced oxygen concentrations.

Increased root density should improve phytoremediation through several mechanisms. Root activities, including water consumption and direct uptake of benzene, toluene, and xylenes (Burken and Schnoor, 1999), could be improved with a greater root density. The rhizosphere effect could also be positively influenced by higher root density. The rhizosphere, defined as the zone of soil immediately adjacent to roots (soil within 1 mm of roots), contains a rich organic mixture of root exudates, leaked and secreted compounds, mucilage, and sloughed dead cells that allows for the proliferation of soil microorganisms (Lynch, 1990). Studies have shown increases in rhizosphere microbial populations over nonrhizosphere populations to be on the order of 4 to 100 times (Chaineau *et al*., 2000; Crowley *et al*., 1996; Jordahl *et al*., 1997).

Phytoremediation is typically used for residual contaminant concentrations at shallow soil depths (Schnoor *et al*., 1995). The effectiveness is hindered by contaminant "smear zones," stained layers that form when petroleum hydrocarbons are sorbed in the unsaturated zone or when floating organic contaminants rise and fall with the water table. Relatively high total petroleum hydrocarbon (TPH) concentrations and anaerobic conditions often characterize these petroleum smear zones (Lee *et al*., 2001).

This situation was present at a phytoremediation demonstration site in Heath, Ohio, where soil gas measurements were used to determine the penetration of oxygen into a hydrocarbon smear zone. During the first 2 years of monitoring, only gas samples collected from a depth of 0.0- to 0.6-m (0- to 2-ft) below grade show the presence of oxygen. Deeper samples have oxygen concentrations below the detection limit of 0.1% (vol). A typical soil gas profile for the Heath, Ohio, site is shown in Figure 1 (Ashland and Unocal, 2000). Carbon dioxide and methane concentrations of 10 to 30% (vol) are also commonly present, indicating strong anaerobic conditions. After 2 years of growth, poplar tree roots were unable to penetrate the smear zone (Figure 2). This motivated experiments to determine whether the lack of root formation could stem from toxicity, oxygen stress, or both.

Nutrient limitations are also prevalent in organic-contaminated soils. As microorganisms degrade contaminants, nitrogen and phosphorus supplies are consumed. These nutrient deficiencies can hinder plant growth and limit microbial degradation of contaminants. However, researchers have also observed diminished rates of microbial biodegradation after the addition of nitrogen and phosphorus amendments, and attributed this phenomenon to inhibition of oligotrophic degraders or to the stimulation of noncompetent bacteria (Entry *et al*., 1993; Johnson and Scow, 1999; Morgan and Watkinson, 1992). This suggests that nutrient amendments for enhanced microbial degradation should be considered when site data confirms nutrient limitation. The nutrient amendments used in this study were used to establish a healthy stand of hybrid poplar trees in Heath, Ohio, soil. Nutrient amendments were not evaluated with respect to microbial degradation.

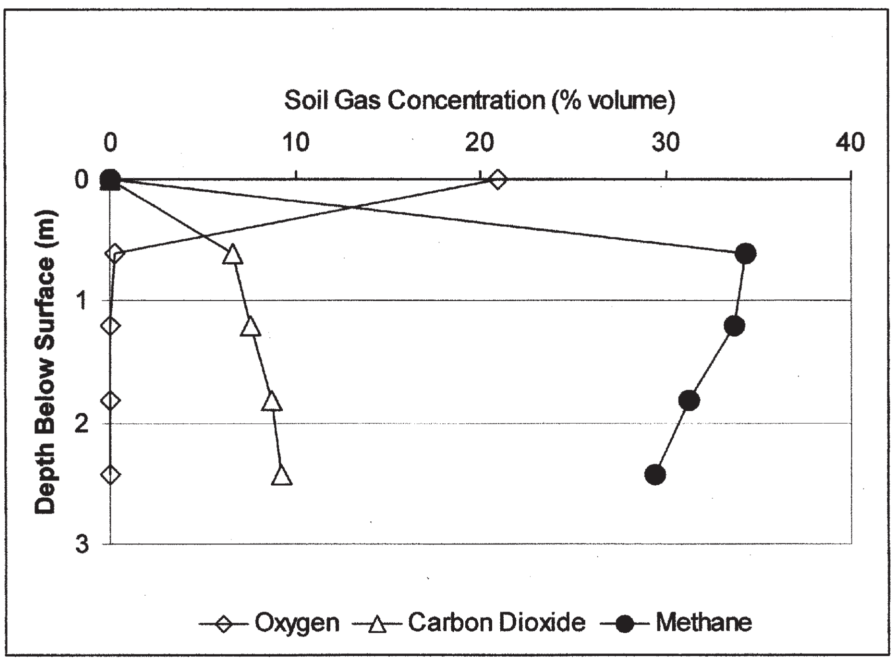

FIGURE 1. Typical soil gas profile observed for one of five sampling points at the Heath, Ohio phytoremediation demonstration site. Hydrocarbon-stained soil was observed for depths of 0.6 m to 3.64 m. Anaerobic methanogenic conditions were observed below 0.6-m depth.

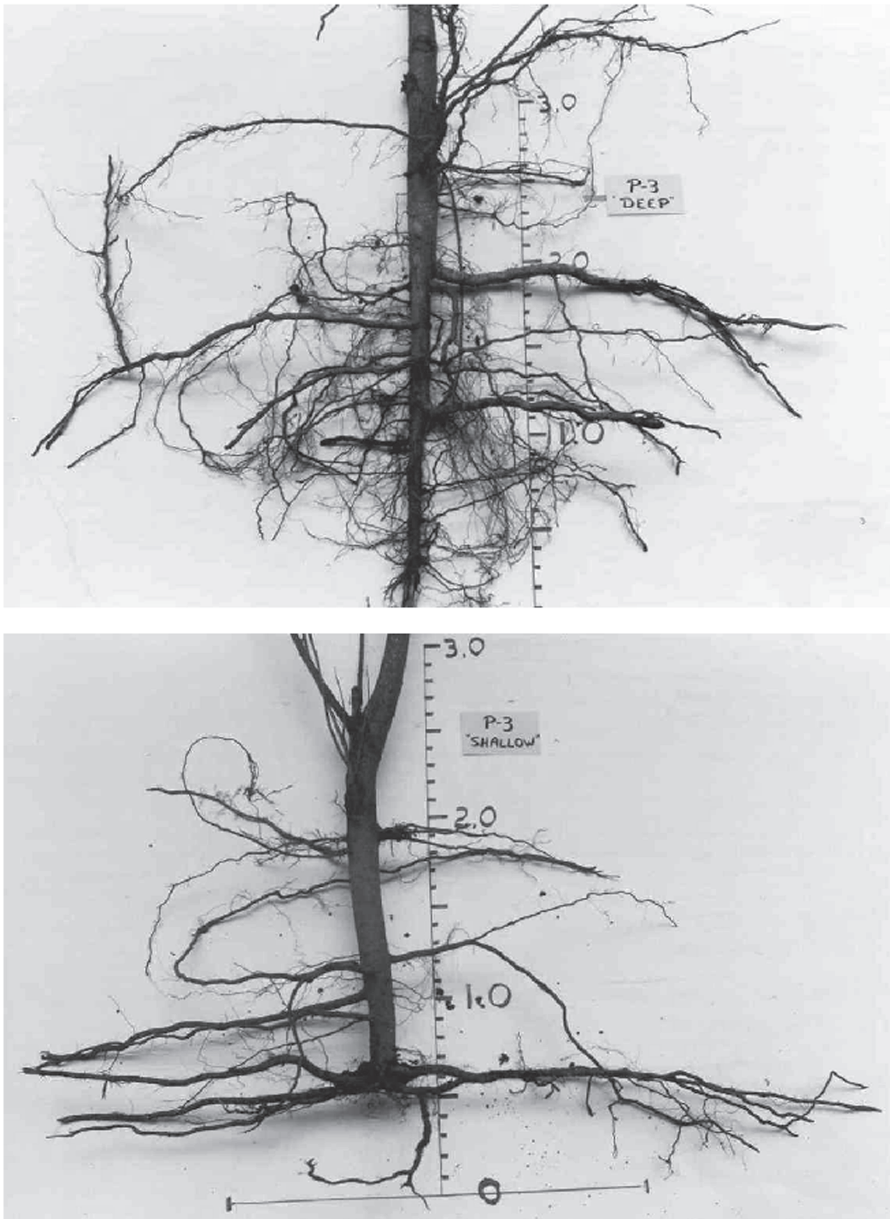

FIGURE 2. Two-year-old poplar root masses excavated from the Heath, Ohio, phytoremediation site. Panel A shows root penetration of 0.9 m and panel B shows 0.8 m of root penetration; each stops short of the smear zone (1.0 m depth).

This article presents greenhouse studies using contaminated site soil and hybrid poplar trees. The purpose of this research was twofold: (1) to develop a treatability approach for testing soil amendments in the greenhouse prior to full scale planting, and (2) to assess the relative importance of nutrient and oxygen addition on hybrid poplar growth using site soils. Potential phytotoxicity of site soil was examined during the treatability study. A separate oxygen addition study was conducted to characterize the response of hybrid poplar trees grown in smear zone soil to passive methods of subsurface oxygen addition.

II. MATERIALS AND METHODS

A. Soils

Soils from the phytoremediation demonstration site in Heath, Ohio, were contaminated with total petroleum hydrocarbons (TPH) at depths ranging from 0.9 to 4.5 m (3 to 15 ft). Concentrations in this zone ranged from 820 to 11,000 mg/kg for gasoline range organics TPH and 1500 to 4400 mg/kg for diesel range organics TPH. Previous nutrient analysis of the Heath soils (Table 1) showed possible nitrogen and phosphorus deficiencies (Ashland, 2000). Two soils were obtained from Heath, Ohio, on July 29, 1999 using a backhoe and 208-L (55-gallon) drums and were shipped to the University of Iowa Oakdale Campus greenhouse. Upper Heath (UH) soil was excavated from a depth of 0 to 0.6 m (0 to 2 ft) and smear zone (visibly stained by hydrocarbons) soil was excavated from a depth of 1.8 to 2.4 m (6 to 8 ft).

B. Treatability Study

UH soil was placed into 26.5-L (7-gal) pots and amended with 1 of 11 fertilizer treatments (Table 2). Each amendment condition was tested in triplicate. All fertilizers were purchased from Pleasant Valley Garden Center, Iowa City, Iowa. Imperial Carolina hybrid poplar (*Populus deltoides* × *nigra* DN34) cuttings, the genetic clones

Table 1. Heath Site Soil Conditions

	Upper Heath Soil	Smear Zone Soil	Method
Texture	Loam	Loam	
pH	6.0 +/- 0.8	5.3 +/- 0.7	1:1 soil:water solution with glass electrode
CEC (meq/100g)	15.5 +/- 0.7	12.5 +/- 3.5	Standard 1 N ammonium acetate
NO^3-N (ppm)	2.8 +/- 1.5	2.0 +/- 1.5	Single Potassium Chloride extract analyzed colorimetrically
NH^3-N (ppm)	11.5 +/- 5.8	14.4 +/- 7.4	
P (ppm)	18.8 +/- 4.2	19.7 +/- 8.7	Single Ammonium Acetate extract analyzed via inductively coupled plasma spectroscopy
K (ppm)	100.7 +/- 28.3	97.7 +/- 21.7	
Ca (ppm)	1553.7 +/- 520.4	1113.6 +/- 335.1	
Mg (ppm)	195.0 +/- 68.3	161.6 +/- 42.3	

UH soil (n = 18) and smear zone soil (n = 27)

Analysis by Western Labs, Parma, ID

Table 2. Treatability Study Amendments

Condition	Amendment	Application Rate		Nutrient Source
		lbs/acre	kg/ha	
Control	Site soil without amendments			
N-50	50/50 mix of inorganic and organic nitrogen	50	56	Hi Yield® Blood Meal and Hi Yield Ammonium Sulfate
N-100		100	112	
N-150		150	168	
P-50	Phosphorus	50	56	Hi Yield® Super Phosphate
P-100		100	112	
P-150		150	168	
NPK	Nitrogen	100	112	Greenview® 10/10/10 NPK
	Phosphorus	100	49	
	Potassium	100	93	
Mg	Mg^{2+}	218	244	Glorious Gardens® Magnesium Sulfate
Ca	Ca^{2+}	22	24	Hofman® Gypsum
All	All Amendments (NPK, Mg, and Ca)	as above		as above

of those planted in the field, were obtained from Hramor Nursery, Manistee, MI. Three 61-cm (24-in) bare-root cuttings (172 ± 45.4 g average mass per pot) were planted in each pot. After 3 weeks of growth, five cuttings did not bud and were replaced with new cuttings. The cuttings were watered every 2 to 3 days with approximately 1.0 L of tap water throughout the 97-day growth period. Heat (day: 24.7 ± 5.5°C; night 14.7 ± 2.7°C) and light (61.6 lumens/m^2 at soil surface) were provided in the greenhouse by lamps operating on a 10-h daily cycle. At the end of the study, all of the soil was washed from the roots of the plants and the mass of the plant was recorded. Photographs of each plant and selected root masses were also taken at the conclusion of the study.

C. Oxygen Addition Study

Soils were loaded into solid Advanced Drainage Systems, Inc. (ADS) tubing (black corrugated nonperforated polyethylene plastic) with a diameter of 20.3 cm, fitted with an ADS cap, and all of the seams sealed with duct tape (Figure 3). Four 0.32-cm holes were used for drainage, and each growth tube was placed in a dish filled with water to minimize oxygen transfer. Growth tubes contained 30.5 cm (12 in) of moist smear zone soil on top of 15.2 cm (6 in) of drainage gravel, with moist UH soil filling the remaining 45.7 cm (18 in). Soils in each treatment were packed in the same manner except for the one trial where ORC was mixed into smear zone

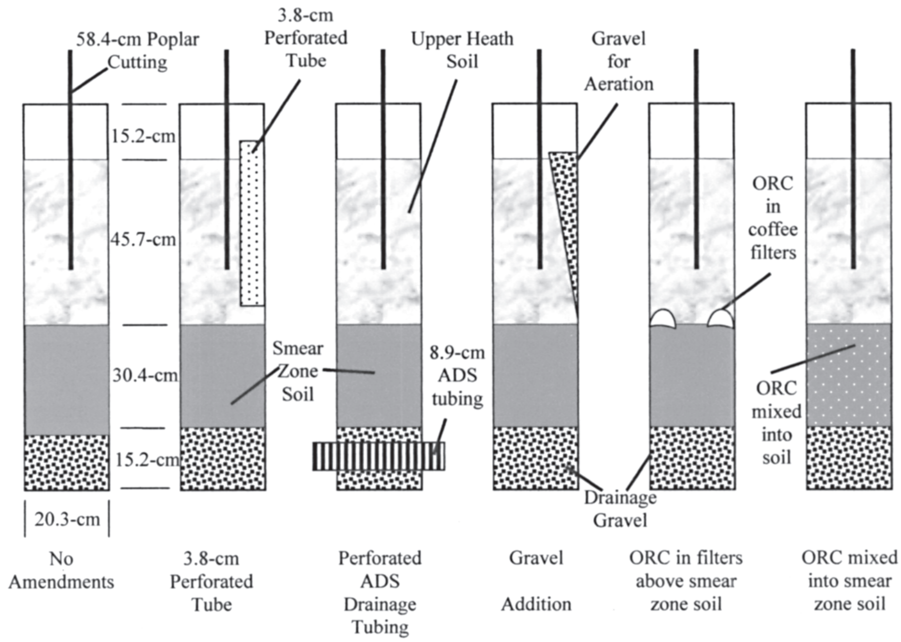

FIGURE 3. Configuration of growth tubes with various oxygen delivery methods.

soil. In this trial, the smear zone soil was mixed with ORC before being packed into the growth tubes. Five different passive oxygen delivery methods were added to the growth tubes as soils were loaded (Figure 3).

- 3.8-cm Perforated tube
- Perforated ADS drainage tubing
- Gravel addition
- Oxygen Release Compound (ORC) placed in filters above smear zone soil
- ORC mixed into smear zone soil

These were considered to be practical, relatively inexpensive methods for oxygen addition.

The perforated aeration tube (placed to one side of the growth tube) supplied oxygen to upper roots, which could be transferred by the root system into the smear zone. This design could be easily implemented in the field during planting (Ferro *et al*., 2001). Perforated ADS tubing (8.9 cm diameter, perforated, black corrugated polyethylene tubing) was placed below smear zone soil for the transfer of oxygen into the smear zone. In the field, perforated tubing could be placed in the planting trench before backfilling. Gravel was added to UH soil (gravel, occupying one-fourth of the tube volume, was placed on one side of the tube to the depth of the smear zone soil) to allow atmospheric levels of oxygen in the soil above the smear zone. In the field this could be accomplished when backfilling the planting trench.

Oxygen Release Compound (ORC) was used in two designs to provide subsurface oxygen. ORC, a white powder with magnesium peroxide as the active ingredient, slowly releases oxygen when in contact with water.

$$2MgO_2 + 2H_2O \Rightarrow 2Mg(OH)_2\ (s) + O_2$$ (Koenigsburg and Norris, 1999)

Many successful remediation efforts have been accomplished using ORC as an electron acceptor for organic contaminants (Koenigsburg and Norris, 1999). Here, ORC (96 g per tube, split between two filters) was placed in filters (an unbleached flat coffee filter was folded, creating a pocket; the edges were kept together with clear tape) just above the smear zone, similar to the application of ORC in the field (Koenigsburg and Norris, 1999). Again, oxygen was supplied to roots in the upper soil with the possibility that the plant would transfer oxygen to the smear zone. ORC (96 g per tube) was also mixed into the smear zone to ensure oxygen availability for poplar roots (not a typical field application of ORC). Regenesis Bioremediation Products, Inc. (San Clemente, CA) supplied ORC.

One 58-cm (23-in) DN34 hybrid poplar bare-root cutting (106 ± 34.9 g average mass) was planted in each growth tube. Each delivery method was tested in triplicate except for gravel addition and ORC mixed into smear zone soil, where one trial was used due to shortage of smear zone soil. Approximately 500 mL of tap water was supplied every 2 to 3 days during the 100-day growth period. As before, heat (day: 24.7 ± 5.5°C; night 14.7 ± 2.7°C) and light (61.6 lumens/m^2 at soil surface) were provided by lamps operating on a 10-h daily cycle. At the conclusion of the experiment, photographs were taken to record effects. Plastic tubes were cut away from the soil, and the soil was divided into 15.2-cm (6-in) segments. Roots were recovered by washing away soil with copious amounts of water. Root mass was recorded for towel-dried roots for each 15.2-cm segment, as was above-ground biomass. No fertilizers were used in any growth tubes.

D. Statistical Analysis

Student's t-test (Hogg, 1987) was performed at the 95% level to determine whether biomass growth or root density increases were significantly different for various treatments compared with unamended controls. For the ORC mixed into smear zone soil and gravel addition treatments, which did not have replicates, statistical significance was determined by comparison to the upper 95% confidence limit for the control set.

III. RESULTS AND DISCUSSION

A. Treatability Study

The net biomass (final minus initial plant mass) of hybrid poplars grown in UH soil with nitrogen amendments (N-50, N-100, N-150, NPK, and "All-amendment" treatments) was significantly higher ($p < 0.05$) than control plants grown with no amendments (Figure 4). In contrast, other amendments (i.e., P, Mg, and Ca) did not have a statistically significant effect on plant growth. The results indicate that nitrogen amendments are required to enhance the growth hybrid poplar trees at the Heath, Ohio, site.

Photographs taken of each plant at the end of the growth period showed stimulation of poplar growth with nitrogen additions. The leaves of the plants grown with nitrogen were broad and dark green, indicating good health. Conversely, plants grown with phosphorus amendments alone were narrow and yellow. Although plants grown with higher nitrogen concentrations grew increasingly taller with more leaf mass (Figure 5), biomass standard deviations were relatively high, and no statistically significant differences were established between these nitrogen treatments. Based on visual observations of increased stimulation with additional nitrogen, a 10/5/5 NPK fertilizer mixture applied at 1121 kg/ha (112 kg-N, 24.4 kg-P, 46.5 kg-K per ha) was chosen to enhance hybrid poplar growth at the Heath site. An NPK fertilizer was chosen for robustness, and the 10/5/5 ratio was chosen to emphasize the known high requirements of hybrid poplar for nitrogen (Heilman *et al.*, 1998). No obvious soil toxicity effects were observed in any treatment.

B. Oxygen Addition Study

The growth of hybrid poplars in UH and smear zone soil was monitored using whole plant biomass and root density. The net biomass (final minus initial plant

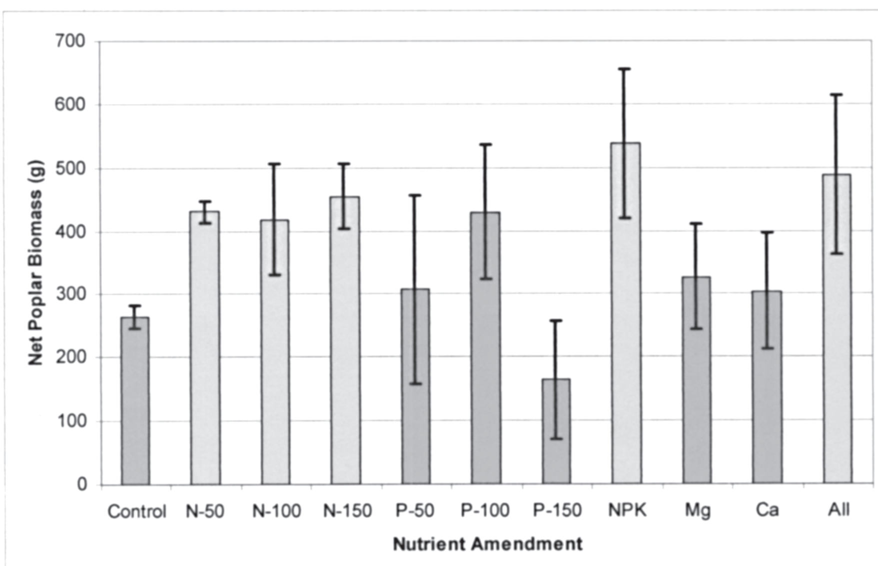

FIGURE 4. Net biomass of hybrid poplar trees grown in UH soil with various nutrient amendments. Error bars represent one standard deviation from the mean of triplicate pots. Hashed bars are statistically different from control pot ($p < 0.05$). Hashed bars were statistically indiscernible from one another ($p < 0.05$).

FIGURE 5. Representative plants with increasing concentrations of nitrogen addition. Bars show 15.3-cm increments. N – 50 represents 56 kg N/ha (50 lb N/acre) fertilizer.

mass) increased significantly ($p < 0.05$) when compared with controls when ORC was placed in coffee filters above the smear zone soil (Figure 6). No significant changes in biomass were observed for the other treatments. However, the biomass grown when ORC was mixed into the smear zone soil was 548 g, a significant outlier to the 95% confidence interval for control pots of 223 ± 27.8 g. This corroborates that oxygen addition can significantly stimulate poplar growth in smear-zone soil.

Hybrid poplar biomass for the ORC mixed into smear zone soil treatment resulted in a 2.46-fold increase, and the ORC in filters treatment showed a 1.45-fold increase over control pots (Table 3). These control-normalized increases in biomass were similar to those observed in the treatability study with nitrogen addition (1.58- to 2.03-fold increases). This suggests that overcoming oxygen limitation (resulting from petroleum contamination) is as important to poplar growth as nitrogen fertilizer addition. Note that plants were grown in the treatability study using shallow pots and soil with minimal petroleum contamination, where no oxygen limitation should have occurred. However, no nutrients were added to soil in the oxygen study, and plant growth may have been nutrient limited.

Fine roots were observed in the lowest 6 in. of smear zone soil for each treatment. This contrasted with field observations of no root penetration in the smear zone (Figure 2). Layer compaction may have inhibited root growth at the Heath, Ohio, demonstration site. The inability to pack soils to the degree of the field in this study may have led to some of the observed root growth. However, the role of oxygen addition seemed much more important, as seen relative to controls. The observation of fine roots throughout smear zone soil for all treatments suggested soil toxicity may be of little concern for hybrid poplar trees in contaminated Heath, Ohio, soils.

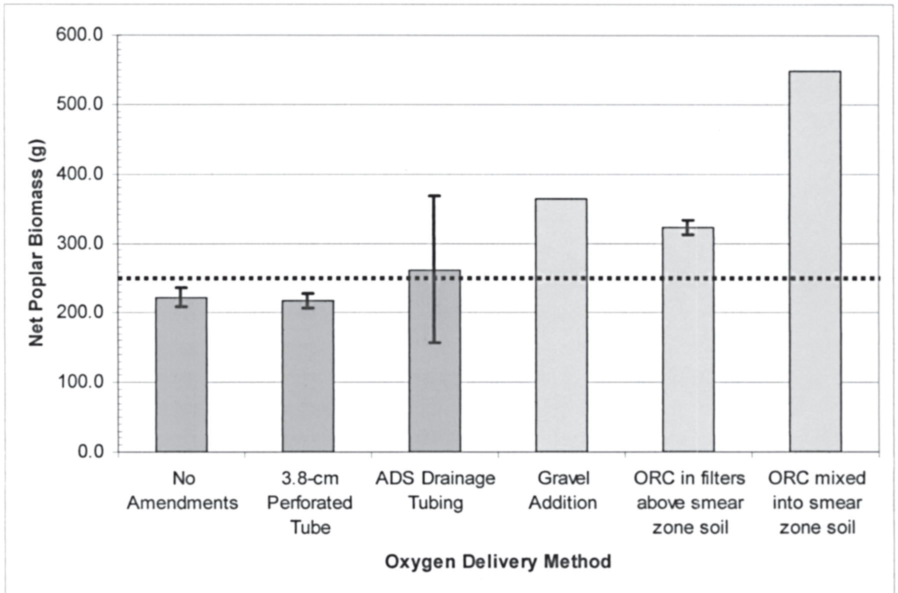

FIGURE 6. Net biomass for poplars grown in UH and smear zone soil with various oxygen delivery methods. Error bars represent standard deviation from the mean of triplicate pots. Hashed bar was statistically different from the control (< 0.05). The dashed line represents the upper limit of a 95% confidence interval for the control (250.4-g). One trial was used for gravel addition and ORC mixed into smear zone soil. No nutrient amendments were included.

Table 3. Biomass Growth, Normalized to Controls*

Treatability Study	g/g	Oxygen Study	g/g
Control	1.00	No amendment	1.00
N-50	1.63	1.5'' Perforated tube	0.98
N-100	1.58	ADS Drainage tubing	1.18
N-150	1.72	Gravel addition	1.64
P-50	1.16	ORC in filters above smear zone soil	1.45
P-100	1.63	ORC mixed into smear zone soil	2.46
P-150	0.62		
NPK	2.03		
Mg	1.24		
Ca	1.15		
All	1.85		

*97-day treatability study and 100-day oxygen amendment study

Root density was calculated using towel-dried root mass from 15.2 cm segments of the growth tubes (Figure 3). The volume of the segments was calculated using a height of 15.2 cm and a tube diameter of 20.3 cm. Segments from 0 to 45.7 cm below grade contained UH soil. Smear zone soil was located from 45.7 to 76.2 cm below grade and roots obtained in the drainage gravel were 76.2 to 91.4 cm below grade.

No change in root density was observed for the ADS drainage tubing or the 3.8-cm perforated tube methods of oxygen delivery over controls (Figure 7). The high standard deviation shown for the 76.2- to 91.4-cm (drainage gravel) segment was the result of a root penetrating a 0.32-cm drainage hole and growing in the water collection dish, exposed to saturating concentrations of oxygen. Increased root density compared with controls was measured for the gravel amendment, ORC in coffee filters above smear zone soil, and ORC mixed into smear zone soil growing conditions (Figure 7). In each case, root density was increased for soil segments located above oxygen addition. Gravel addition yielded root density increases for segments from 15.2 to 61.0 cm below grade, which included the top 6 in of smear zone soil (45.7 to 61.0 cm). Here, the porosity of the gravel allowed ambient

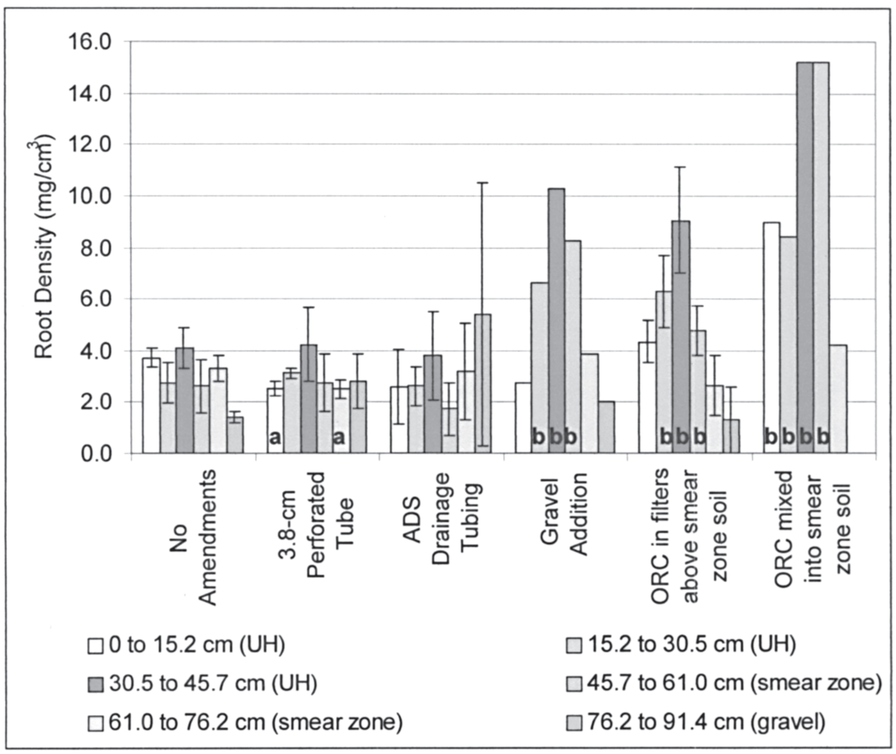

FIGURE 7. Root density of hybrid poplars for oxygen addition study using 15.3-cm soil depth segments. Error bars represent standard deviation from the mean of triplicate pots. Soil depth given below grade. [a]Statistically significant decrease from ($p < 0.05$). [b]Statistically significant increase from controls ($p < 0.05$).

concentrations of oxygen at the surface of the smear zone soil. When ORC was placed in filters above smear zone soil, root density was increased with statistical significance ($p < 0.05$) for three segments of soil from 15.2 to 61.0 cm below grade (Figure 7). When ORC was mixed into smear zone soil, root density was increased for depth intervals from 0 to 61.0 cm below grade. This included the top 15.3 cm of smear zone soil (47.0 to 61.0 cm), where the highest root density was recorded for the entire study with a value of 15.2 mg/cm^3. This value was 3.7 times greater than 4.1 mg/cm^3, the largest root density observed without oxygen addition (45.7 to 61.0 cm).

Increases in root density were attributed to oxygen availability. The reaction of ORC with water produces $Mg(OH)_2$, a solid product capable of increasing soil pH after dissolution and increasing the Mg-exchangeable base cation pool. This could enhance plant growth in acidic soils. However, the pH of UH and smear zone soil (Table 1) was near the optimum range of 5.5 to 8.0 reported for growth of hybrid poplar trees (Braatne, 1996). In addition, root density increases were observed most commonly in soil overlying the ORC layer, which was not in contact with potential high-pH drainage water. Thus, the increases in root densities were attributed to enhanced oxygenation by gaseous O_2 diffusion. It cannot be ruled out, however, that the addition of MgO_2 to soils increased the base exchange capacity and pH of the soil and contributed to enhanced root growth in the smear zone.

ORC (MgO_2) addition to soils results in the addition of Mg(OH) (s) and oxygen to soils. The Mg(OH) (s) is sparingly soluble and will raise the acid neutralizing capacity (ANC) of soils.

$$Mg(OH)_2 \Leftrightarrow MgO\ (s) + H_2O$$

$$ANC = 6(Al_2O_3) + 2(CaO) + 2(MgO) + 2(K_2O) + 2(Na_2O) + 4(MnO_2) + 2(FeO) + NH_4OH - 2(SO_3) - HCl - 2(N_2O_5) \qquad \text{(Schnoor, 1996)}$$

This in turn will add Mg-exchangeable bases to the soil and raise the pH of the soil.

$$Mg(OH)_2 + 2HX \Leftrightarrow MgX_2 + 2H_2O$$

where X is the cation exchange site in the soil complex, HX is the exchangeable acidity, and MgX2 is the Mg-exchangeable base cations in soil. Thus, it is not possible to rule out the importance of ORC to increasing the pH of smear zone soils. However, most of the enhanced root growth was observed in the upper soil (UH).

Another aspect of oxygen addition is microbial respiration. Complete reaction of 96 g ORC yields 0.85 moles of O_2. If 4.4 g/kg TPH DRO (nonvolatile) exerts an oxygen demand of 0.33 mol/kg, oxidation of 6.0 cm of smear zone soil can be accomplished through aerobic degradation (Tube diameter = 20.3 cm, Bulk density ~ 1.3 g/cm^3). This suggests the amount of ORC supplied would be inadequate for the degradation of soil contaminants. However, contaminant concentrations were not measured in this study, with the focus emphasizing the response of poplar trees to various oxygen implementation strategies. The proper design of an enhanced phytoremediation system should include oxygen demands for contaminants, microbial populations, and plants. Ongoing experiments at the University of Iowa are addressing the specific oxygen requirements of hybrid poplar trees growing in smear zone soils.

IV. CONCLUSIONS

Results demonstrate the importance of biomass measurements to evaluate the benefit of soil amendments and to determine application rates that enhance poplar growth in phytoremediation efforts. The developed treatability approach worked well to show differences among treatments and can be used for testing amendments in the greenhouse prior to full-scale field application. The procedures outlined could be used to determine the feasibility of phytoremediation and the proper amendments to improve growing conditions in the field.

Oxygen amendments clearly enhanced the growth of poplar trees and their root systems. Given that oxygen injection for enhanced microbial degradation of petroleum hydrocarbons is often an expensive endeavor, the passive oxygen delivery methods presented here, in conjunction with a phytoremediation system, may offer economic advantages over conventional remediation strategies. The addition of oxygen improved the growth of plants, which should increase contaminant uptake and expand the rhizosphere effect in the field. Passive oxygen delivery could extend the applicability of phytoremediation to soils with smear zones or other contaminants that are difficult to remediate because of their high biochemical oxygen demand.

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