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Influence of soil gas contamination on tree root growth

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Summary Rooted-cuttings and saplings of green ash (*Fraxinus lanceolata*) and hybrid poplar (*Populus* spp) were planted on a former municipal refuse landfill and on a nearby nonlandfill control plot. The root systems of four trees of each species and size were excavated on the landfill plot – two growing in an area where the concentrations of anaerobic landfill gases were relatively high and two in a relatively low-gas area. Two trees of each species and size were also excavated on the control. The root systems of both species were significantly shallower on the landfill plot than on the control. Green ash appeared to avoid the adverse gas environment of the deeper soil layers on the landfill by producing adventitious roots. Hybrid poplar became adapted in a different manner, by redirecting root growth from the deepter soil layers to the soil surface.

Introduction

It has become increasingly common to reclaim completed sanitary refuse landfill sites by converting them into parks, golf courses, botanical gardens, recreation areas or farmland. Great Britain[8] and the United States[1] contain many examples of these reclamation efforts. Most reclamation attempts have been less than completely successful. However, some well planned, properly managed projects to vegetate abandoned dumping sites with trees, shrubs, grass or agricultural crops have been successful in the United States[1].

The factors limiting good growth on completed refuse sites have been intensively studied throughout the United States since 1975[1,2,3]. These include toxicity of landfill generated gases (*e.g.* CO_2) to root systems, low soil oxygen supply, thin cover soil, limited cat. exchange cap., low nutrient status, low water holding capacity, low soil moisture, high soil temperatures, high soil compaction, poor soil structures and sensitive plant species. In a species screening test on a former landfill in New Jersey, hybrid poplar and black gum (*Nyssa sylvatica*) grew significantly better than many other species, whereas, green ash and American sycamore (*Platanus occidentalis*) grew very poorly[4].

This paper reports on those investigations that were designed to determine if the presence of gases of anaerobic refuse decomposition (CO_2, CH_4) affect rooting depth on landfills and to determine if trees planted as seedlings can adapt their root systems to landfills quicker and more effectively than larger seelings.

Materials and methods

In the spring of 1976, ten small specimens (one-year-old) and ten larger specimens (six-year-old stock) of both green ash and hybrid poplar were planted on the Edgeboro Landfill and on a nearby nonlandfill control area, totaling 80 trees. Prior to planting sixty cm of soil had been spread over a 7 m deep municipal refuse landfill and on the control site. After four growing seasons, two randomly selected trees of each species and size on the control, and two trees on the landfill plot from a relatively high (10% CO_2) and two from a relatively low-gas (<6% CO_2) area were studied.

The entire root system of each tree was excavated with a pick and a small hand trowel from the point of emergence at the main stump to the root tips by a modification of Weaver's[9] excavation technique originally used exclusively for field crops. All roots larger than 1 mm were studied except in cases where they had been broken and the end portion of the root could no longer be located.

After an individual root had been exposed, the distance from the soil surface to the center of the root was measured at 30 cm intervals from the stump to and including the root tip. Total length and maximum depth were recorded of all roots except those which were recognized as having been present at the time of planting.

Average depth was calculated for each root system by summing the values recorded at 30 cm intervals and dividing by the total number of measurements. The proportion of total root length in specified depth intervals was also determined for each tree.

The concentrations of O_2, CO_2 and CH_4 were measured at the 20 cm depth at two points around each tree by gas chromatography. Gas samples were collected every two weeks from May through September 1976–1979. Soil moisture was calculated on samples collected from the 0–20 cm depth at two week intervals from several locations on each plot. Soil bulk density was measured at one time in 1978 from a 20 cm soil core from 16 locations on each plot.

Results

Average CO_2 and CH_4 concentrations and temperatures were significantly greater and oxygen and moisture contents significantly lower on the landfill than on the control plot (Table 1).

Root distribution in the landfill soil was significantly different from that in the control plot. Roots of the two small control hybrid poplars were not as concentrated in the top soil layers as those in the landfill plot but were more evenly distributed in the soil than those in the landfill plot (Table 2). Root

Table 1. Soil gas content, moisture, temperature and bulk density in landfill and control soil

Soil variable	Landfill	Control
O_2 (%)	17.0	19.5
CO_2 (%)	8.2	1.2
CH_4 (%)	2.9	0.0
Moisture (% dry wt.)	8.1	11.1
Bulk density (g/ml)	1.6	1.6

Table 2. Frequency of roots of hybrid poplar cuttings (small trees) in each root depth class; total root length, mean root depth, maximum root depth and CO_2, CH_4 and O_2 concentrations* in high and low-gas landfill areas and in no-gas control area

Root depth class (cm)	Root frequency at each depth (%)**		
	Landfill		Control
	High-gas area	Low-gas area	No-gas area
0–1.3	38.8a***	16.2b	0.7c
> 1.3–5.1	38.7	52.2	27.2
> 5.1–10.1	12.3	15.4	18.0
> 10.1–25.4	10.2	10.9	36.3
> 25.4–38.1	0.0	2.0	7.4
> 38.1	0.0	3.3	3.9
Soil gas (%)			
CO_2	18.1	1.4	1.2
CH_4	5.0	trace	0.0
O_2	15.8	19.6	19.4
Root measurements			
Total root length (m)	85.6	96.0	113.5
Mean root depth (cm)	4.8	8.9	13.6
Maximum root depth (cm)	25.4	58.4	55.8

* Means, each from 42 readings collected at the 20 cm depth throughout the 1977–1979 growing seasons. Concentrations are in % by volume and were analyzed on a Carle 8500 gas chromatograph.
** Values represent mean from 2 trees.
*** Columns followed by different letters are significantly different at $P < .01$ by Chi-Square Analysis.

distribution of the poplar cuttings in the high-gas landfill area (18.1% CO_2, 5.0% CH_4, 15.8% 0_2 @ 20 cm depth) was significantly different from that in both the low-gas landfill (CO_2 = 1.4%, CH_4 = 0%, O_2 = 19.6%) and control areas (Table 2). Thirty-nine percent of the poplar roots in the high-gas area were in the top 1.3 cm of soil, whereas, only 16.2% of the roots in the low-gas area and less than 1% of those in the control area were found at the 0–1.3 cm depth. No roots were found below 25.4 cm in the high-gas landfill area; whereas, 5.3% of the roots in the low-gas landfill area and more than 10% of those in the control area were found below this depth. Total root length was only slightly reduced in the high compared to the low-gas landfill area but mean and maximum root depths in the high-gas area were about half that in the low-gas area.

Of four large hybrid poplar (saplings) excavated on the landfill plot, two were

Table 3. Frequency of roots of hybrid poplar saplings (large trees) in each root depth class; total root length, mean root depth, maximum root depth and CO_2, CH_4 and O_2 concentrations* in high and low-gas landfill areas and in no-gas control area

Root depth class (cm)	Root frequency at each depth (%)**		
	Landfill		Control
	High-gas area	Low-gas[3] area	No-gas area
0–1.3	10.2a***	6.4a	0.7b
> 1.3–5.1	42.1	45.6	29.1
> 5.1–10.1	19.1	20.8	20.6
> 10.1–25.4	28.6	25.4	44.8
> 25.4–38.1	0.0†	1.2	3.5
> 38.1	0.0†	0.6	1.3
Soil gas (%)			
CO_2	12.8	3.1	1.2
CH_4	4.8	0.0	0.0
O_2	12.1	18.1	19.1
Root measurements			
Total root length (m)	19.2	52.7	97.5
Mean root depth (cm)	8.6	8.4	12.8
Maximum root depth (cm)	22.8	45.7	49.5

* Means, each from 42 readings collected at the 20 cm depth throughout the 1977–1979 growing seasons. Concentrations are in % by volume and were analyzed on a Carle 8500 gas chromatograph.
** Values represent mean from 2 trees.
*** Columns followed by different letters are significantly different at $P < .01$ by Chi-Square Analysis.
† Both trees died 2 to 4 weeks prior to excavation.

in a high-gas area where the CO_2 concentration at the 20 cm soil depth during the 3-year period 1977–1979 averaged 12.8%; CH_4 4.8%; and O_2 12.1% (Table 3) and two were in a relatively low-gas area (CH_4 = 0.0%, O_2 = 18.1%, CO_2 = 3.1%). The trees in the high-gas area had died two and four weeks respectively prior to excavation and, therefore, many of their roots were no longer living. The roots which remained alive had originated from the stump at a depth of 15 cm or greater and grew toward the soil surface; their ends were located in the top 2.5 cm of the soil profile. Most of the roots in the low-gas landfill area also grew toward the soil surface as they elongated, but few dead roots were found on these trees.

Roots of the excavated control poplars did not tend to grow toward the soil surface as did roots on the landfill areas. Deep roots which were scarce for these trees in the landfill area were not uncommon in the control plot (Table 3). Total root length for poplars in the high-gas landfill area was less than half that of trees

Table 4. Percentage of roots of green ash (small trees) in each root depth class; total root length, mean root depth, maximum root depth and CO_2, CH_4 and O_2 concentrations* in high and low-gas landfill areas and in no-gas control area

Root depth class (cm)	Root frequency at each depth (%)**		
	Landfill		Control
	High-gas area	Low-gas area	No-gas area
0–1.3	0.0a***	0.0b	0.0c
> 1.3–5.1	48.0	26.7	10.8
> 5.1–10.1	36.0	36.7	8.1
> 10.1–25.4	16.0	36.6	52.1
> 25.4–38.1	0.0	0.0	25.0
> 38.1	0.0	0.0	4.0
Soil gas (%)			
CO_2	14.7	5.2	1.1
CH_4	6.1	1.9	0.0
O_2	16.1	17.8	19.8
Root measurements			
Total root length (m)	7.6	9.1	18.5
Mean root depth (cm)	7.5	9.6	21.2
Maximum root depth (cm)	17.8	20.3	43.2

* Means, each from 42 readings collected at the 20 cm depth throughout the 1977–1979 growing seasons. Concentrations are in % by volume and were analyzed on a Carle 8500 gas chromatograph.
** Values represent mean from 2 trees.
*** Columns followed by different letters are significantly different at $P < .01$ by Chi-Square Analysis.

in the low-gas landfill area and trees in both landfill areas produced less total root length than those on the control area. However, there was no significant difference in root distribution between the high-gas area and the low-gas landfill area as there was with the small poplars. Both landfill trees produced over 50% of their roots in the top 5.1 cm of soil; whereas, only 30.5% of the roots were found within this depth on the control.

The roots of the small green ash growing in a high-gas landfill area (CO_2 = 14.7%, CH_4 = 6.1%, O_2 = 16.1%) were also concentrated near the soil surface with 48% of the root system in the top 5.1 cm of soil (Table 4). Roots of the small ash in a low-gas area (CO_2 = 5.2%, CH_4 = 1.9%, O_2 = 17.8%) were more evenly distributed in the soil; only 26.7% in the top 5.1 cm of soil. Total root length, mean root depth and maximum root depth values were slightly lower for the green ash in the high-gas area than for ash in the low-gas area.

Table 5. Percentage of roots of green ash (large trees) in each root depth class; total root length, mean root depth, maximum root depth and CO_2, CH_4 and O_2 concentrations* in high and low-gas landfill areas and in no-gas control area

Root depth class (cm)	Root frequency at each depth (%)**		
	Landfill		Control
	High-gas area	Low-gas area	No-gas area
0–1.3	0.0a***	0.0b	0.0c
> 1.3–5.1	78.9	41.4	26.0
> 5.1–10.1	9.5	15.3	22.5
> 10.1–25.4	3.9	37.5	33.1
> 25.4–38.1	7.7	5.8	18.1
> 38.1	0.0	0.0	0.3
Soil gas (%)			
CO_2	13.1	3.9	1.1
CH_4	7.3	1.3	0.0
O_2	12.3	18.3	19.7
Root measurements			
Total root length (m)	32.0	57.9	94.3
Mean root depth (cm)	6.6	11.9	14.7
Maximum root depth (cm)	38.1	30.5	38.1

* Means, each from 42 readings collected at the 20 cm depth throughout the 1978–1979 growing season. Concentrations are in % by volume and were analyzed on a Carle 8500 gas chromatograph.
** Values represent mean from 2 trees.
*** Columns followed by different letters are significantly different at $P < .01$ by Chi-Square Analysis.

Root depth and length values for small ashes in both the high and low-gas areas were approximately half the values of the control. There was little difference in depth and length between the two trees on the control plot. The small ash seedlings on the control area did not form the matted short-root zone found on the landfill trees. In contrast, several control roots grew almost straight downward.

The two large green ash saplings growing in a high-gas landfill area (CO_2 = 13.1%, CH_4 = 7.3%, O_2 = 12.3%) produced a dense mat of short roots at about the 25.4 cm soil depth (Table 5). Immediately below the root mat was a dark soil layer which had the putrid odor of decomposing refuse. A les-dense mat-like formation was found on the ash trees growing in the low-gas landfill area (CO_2 = 3.9%, CH_4 = 1.3%, O_2 = 18.3%). A large portion of the roots in the high-gas area were found in the top 5.1 cm of soil.

Discussion

It has been previously reported[7] that small trees appeared to be more capable of adapting to landfill conditions than large specimens of the same species. The reasons for this were unclear. In the current studies, the biggest difference between the large and small trees other than size was that the small trees were planted with a very shallow root system (about 10 cm deep), and therefore, probably had to become adapted to the landfill soil to a lesser degree than did the saplings which began with a much deeper root system (30–40 cm). The soil environment in the high-gas area may have been adverse for the root growth of larger trees causing death before the roots reached the surface. The smaller trees, on the other hand, had a decided advantage (a shallow root system) in establishing themselves on the landfill. Very little root death was detected on these trees.

The deep roots (30 cm) of both small and large green ash in the high-gas areas did not die as did the roots of the large poplar in the high-gas area. Instead, many short, stunted roots were formed at these deeper soil layers. Another root modification of both large and small ash in the high-gas areas, not found in the low-gas or control areas and not characteristic of poplars, was the production of a shallow set of adventitious roots originating at the trunk approximately 2.5 cm below the soil surface. Consequently, roots of both cuttings and saplings of this species appear to have adapted themselves to the landfill soil conditions in a manner very different from hybrid poplar. Whereas, poplar roots originating at the deeper soil strata on the landfill (30–40 cm) attempted to make their way upward as they elongated, apparently avoiding the adverse gas environment in the deeper soil layers, the deeper green ash roots did not reach for the soil surface but, instead, remained at their original depth where growth continued in a stunted fashion. A shallow root system was established by root formations originating at the root collar. Since green ash roots can reportedly tolerate low oxygen environments[2,6], it is not surprising that the deeper roots apparently tolerated, though did not thrive, in soil containing high landfill gas concentration (CO_2 = 13.1%, CH_4 = 7.3%, O_2 = 12.3%). Future investigations may study the physiological changes occurring in this matted, short and thickened root layer.

This study presents evidence that (1) roots of green ash and hybrid poplar grow significantly closer to the soil surface in landfill cover soil than in nonlandfill soil and (2) small specimens of hybrid poplar can better adapt their root system than large poplars to landfill conditions, but roots of small ash do not appear to be capable of adapting better than those of large ash. The inability of large poplar to adapt themselves to the landfill environment appears to be related to the inability to produce the vitally needed shallow root system quickly enough to avoid the high CO_2 and CH_4 concentrations and low O_2 concentrations characteristic of landfill cover soils. Small poplar produced a shallow root system from roots remaining shallow and from deeper roots growing toward the soil surface. Large and small green ash became adapted to the dumpsite soil also by producing a shallow root system but these roots emanated from the root collar. These data indicate that there may be more than one mechanism for adapting to landfill soils which are not unlike those mechanisms found for flood tolerant species[6].

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