Aspen Response to Forest Soils Amended with Municipal and Industrial By-products on Two Northern Minnesota Sites: Experimental Design and Preliminary Results[1]

by

Molly A. Cavaleri and Daniel W. Gilmore[2]; Morteza Mozaffari[3];
Carl J. Rosen and Thomas R. Halbach[4];
and Russell D. Mathison and Timothy C. O'Brien[5]

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[2]Department of Forest Resources, College of Natural Resources, University of Minnesota, St. Paul, MN.

[3]Department of Crop, Soil, and Environmental Sciences, University of Arkansas.

[4]Department of Soil, Water, and Climate, College of Agriculture, Food, and Environmental Sciences, University of Minnesota, St. Paul, MN.

[5]North Central Research and Outreach Center, University of Minnesota, Grand Rapids, MN.

For more information about the Department of Forest Resources and its teaching, research, and outreach programs, contact the department at:

Department of Forest Resources
University of Minnesota
115 Green Hall
1530 Cleveland Avenue North
St. Paul, MN 55108-6112
Ph: 612-624-3400
Fax: 612-625-5212
Email: forest.resources@umn.edu
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Table of Contents

Abstract

The utilization of municipal and industrial by-products as forest soil amendments can improve forest soil fertility. In this field study, aspen (*Populus tremuloides* Michx.) seedlings were planted at two forested sites (Itasca and Carlton counties) amended with treatments of biosolids, boiler ash, and inorganic agricultural fertilizers. Experimental treatments included biosolids at rates equivalent to 70, 140, 210, and 280 kg available N ha^{-1}, two types of boiler ash (application rates based on % Effective Neutralizing Power), boiler ash plus biosolids, and an untreated control. Preliminary results are reported for soil properties, aspen seedling survival, height, and caliper. Soil pH decreased with increased N application from both biosolids and fertilizer sources, but increased through additions of boiler ash and lime. Soil P increased with increased biosolids and ash application rates. Soil K increased with ash and K fertilizer applications. No differences were detected in aspen seedling survival among treatments at the conclusion of the first and second growing seasons at either installation. Height differences among treatments were detected through ANOVA in 2000 and 2001, but were inconclusive. Aspen height and caliper growth in Carlton County was greater than in Itasca County.

Introduction

Increasing human population densities and increased environmental concerns surrounding the disposal of municipal and industrial waste in landfills have prompted research in the beneficial use of by-products. Greenhouse studies are extremely helpful in examining the effects of early growth in detail, but long-term field installations are necessary to assess changes is soil, plant, and soil water composition over time. Two study sites, one in Itasca County and one in Carlton County, on lands owned by the University of Minnesota were amended with biosolids, boiler ash, and inorganic fertilizers and then planted with aspen seedlings. The objectives for this study are:

- To examine preliminary effects of by-product application and co-application in the field on seedling survival, soil properties, and soil water properties;

- To determine rates of application of municipal and industrial by-products that will provide optimal enhancement of aspen growth (*Populus tremuloides* Michx.) on two forested sites; and

- To monitor long-term changes in soil properties, plant growth, and soil water composition.

Materials and Methods

Itasca County Site

The Itasca County site is on the University of Minnesota North Central Research and Outreach Center and is approximately 1 acre in size. Approximate longitude 47° 14' N and latitude 93° 31' W. Legal description: NW _ of Sec 15, T 55 N, R 25 W in Grand Rapids Township. Lands in Itasca County were cleared of forests and converted to agricultural uses during the mid-1800s. Poor productivity forced the abandonment of these lands and they succeeded into hardwood stands that were high-graded for firewood and saw timber. Attempts to establish forest plantations at the North Central Research and Outreach Center during the turn of the century were moderately successful. Most of the forest was unmanaged until the 1950s when low-grade hardwoods were converted to conifer plantations over an approximate 40-year period. The site used in this study was converted to a Ponderosa pine (*Pinus ponderosa* Laws.) plantation in 1970 that was clearcut during December 1999. Site preparation consisted of stump uprooting and piling of slash under dry conditions during the spring of 2000.

Carlton County Site

The Carlton County site is on the University of Minnesota Cloquet Forestry Center and is approximately 1.5 acres in size. Approximate longitude 46° 42' N and latitude 92° 31' W. Legal description: NW _ of Sec. 31, T 49 N, R 17 W in Cloquet Township. The mature pine forests in Carlton County were harvested during the late-1800s and early-1900s. The research forest at the

Cloquet Forestry Center was established in 1909. The site used in this study has been continuously forested, although it was subjected to unregulated timber harvest around the turn of the 20th century. A mixed-species hardwood and conifer stand was clearcut during the winter of 1999. Site preparation consisted of stump uprooting and piling of slash under dry conditions during the spring of 2000.

Select physical and chemical properties (Table 1) for each site were obtained from composite samples collected during October 1999 prior to the harvest of the Itasca County site and following harvest and a glyphosate site preparation treatment at the Carlton County site.

Table 1. Select pretreatment physical and chemical soil properties.

Soil Property	Unit	Carlton County	Itasca County
Mapping unit		Omega loamy sand	Itasca-Goodland silt loam
Soil texture		Sandy loam	Silt loam
pH		5.1	5.7
buffer pH		6.3	6.6
Total N	%	0.07	0.07
NO_3	mg kg^{-1}	3.4	0.22
NH_4	mg kg^{-1}	2.3	0.77
Organic matter	%	1.3	1.4
Bray P	mg kg^{-1}	56	77
Olsen P	mg kg^{-1}	25	30
Exchangeable Ca	mg kg^{-1} (CEC, cmol(+) kg^{-1})	318 (1.59)	524 (2.61)
Exchangeable Mg	mg kg^{-1} (CEC, cmol(+) kg^{-1})	52 (0.43)	41 (0.34)
Exchangeable K	mg kg^{-1} (CEC, cmol(+) kg^{-1})	65 (0.16)	60 (0.15)

Experimental Treatments: By-products

Before application, each by-product amendment was characterized by the University of Minnesota Department of Soil, Water, and Climate Research Analytical Laboratory (Table 2). Total elemental content was determined using EPA methods # SW 846-3051 (US EPA, 1992). K and P were determined by methods described by the Association of Official Analytical Chemists (AOAC) (Johnson 1990a,b).

Table 2. Elemental composition of boiler ashes and anaerobically digested biosolids.

		Minnesota Power Ash		Potlatch Cloquet Ash		Wisconsin Biosolids	
Constituent[a]	**Unit**	**Mean**	**Range**	**Mean**	**Range**	**Mean**	**Range**
Total C (TC)	%	0.82	0.48 - 1.14	14.6	13.8 - 15.3	16.1	15.2 - 16.6
Total N (TN)	%	0.03	0.01 - 0.04	0.19	.18 - 0.20	3.66	3.65 - 3.70
TC:TN		32.8	28.5 - 48.0	76.6	76.5 - 76.7	4.39	4.15 - 4.48
K	g kg^{-1}	19.2	12.3 - 25.8	36.1	36.1	1.4	1.3 - 1.4
Ca	g kg^{-1}	105	86 - 128	183	182 - 184	54.0	53.0 - 54.0
Mg	g kg^{-1}	11.8	9.8 - 13.8	113	112 - 114	5.2	5.1 - 5.2
P	g kg^{-1}	3.1	2.4 - 3.9	3.7	3.6 - 3.8	22.1	21.9 - 22.3
S	g kg^{-1}	8.2	3.9 - 12.9	29.5	29.4 - 29.6	16.9	16.6 - 17.4
Na	g kg^{-1}	8.9	6.0 - 11.3	9.2	8.9 - 9.5	2.1	1.7 - 2.8
Fe	g kg^{-1}	34.3	27.6 - 40.3	4.9	4.7 - 5.1	19.9	19.8 - 20.1
Al	g kg^{-1}	16.7	14.8 - 18.1	27.5	26.0 - 28.9	39.8	38.8 - 40.6
Mn	g kg^{-1}	1.8	1.4 - 2.1	1.0	1.0	4.5	4.4 - 4.6
Si	g kg^{-1}	1.4	0.7 - 2.7	0.8	0.7 - 1.0	3.3	3.0 - 3.9
Sr	mg kg^{-1}	523	440 - 614	590	586 - 594	677	670 - 683
Ba	mg kg^{-1}	1053	808 - 1301	929	926 - 933	378	377 - 380
B	%	0.82	0.48 - 1.14	14.6	13.8 - 15.3	16.1	15.2 - 16.6
Ti	mg kg^{-1}	932	758 - 1109	2735	279 - 4191	1011	996 - 1022
Zn	mg kg^{-1}	1577	804 - 2382	1356	1348 - 1364	437	435 - 439
Cu	mg kg^{-1}	94.6	67.9 - 131.2	50.7	49.1 - 52.3	542	538 - 546
Mo	mg kg^{-1}	5.5	3.2 - 8.6	<1.5	<1.5	24.1	23.0 - 24.6
Ni	mg kg^{-1}	40.4	32.2 - 47.7	8.9	8.3 - 9.6	28.8	28.2 - 29.5
Li	mg kg^{-1}	10.9	9.2 - 12.4	13.3	12.8 - 13.9	6.6	6.2 - 6.8
V	mg kg^{-1}	54.6	45.7 - 62.3	20.7	20.4 - 21.1	32.5	32.2 - 32.8
Cr	mg kg^{-1}	82.3	44.8 - 136.3	21.9	19.1 - 24.7	60.7	59.2 - 62.9
Rb	mg kg^{-1}	<528	<524 - <530	<354	<354	<530	<528 - <532
Pb	mg kg^{-1}	57.4	29.3 - 83.1	<11.2	<11.2	45.8	45.2 - 46.4
Co	mg kg^{-1}	13.5	11.5 - 15.4	4.3	3.6 - 4.9	10.3	9.8 - 10.6
As	mg kg^{-1}	21.5	12.7 - 28.6	<5.2	<5.2	8.8	7.8 - 9.8
Cd	mg kg^{-1}	5.7	3.0 - 8.6	8.4	8.3 - 8.5	1.7	1.4 - 2.0
Be	mg kg^{-1}	0.5	0.4 - 0.6	0.4	0.4	0.6	0.6

[a] All concentrations preceded by < were below the analytical detection limits for the respective chemical constituent(s).Treatments were chosen to compare various effects: by-products as compared to inorganic fertilizers, biosolids at different rates, and co-applications of ash and biosolids (Table 3). Treatments were randomized within each of four replicates. Replicates were located to ensure minimal changes in environmental conditions within a replicate. Each replicate plot was 83.61m^2 (9.14 x 9.14 m) and separated by 3.05 m wide buffer strips. The Carlton site had 14 treatments (Fig. 1), while the Itasca site had 12 treatments (Fig. 2). Soil amendments were applied as a top dressing at the Itasca County site on June 5 and 6, 2000, and at Carlton County site on June 7 and 8, 2000. Each amendment was spread evenly over the entire area of each plot. Biosolids were spread with rakes and all other materials were spread by hand.

Table 3. Experimental treatments.

ID	Lysimeter Treatments	Treatment description	Treatment abbreviation
1	x	Control, no amendment	Ctrl
2	x	Biosolids @ 70 kg N ha^{-1} [a/]	70 kg N ha^{-1} Bio
3	x	Biosolids @ 140 kg N ha^{-1}	140 kg N ha^{-1} Bio
4	x	Biosolids @ 210 kg N ha^{-1}	210 kg N ha^{-1} Bio
5	x	Biosolids @ 240 kg N ha^{-1}	240 kg N ha^{-1} Bio
6		Minnesota Power Ash [b/]	MN ash
7		Biosolids @ 140 kg N ha^{-1} +Minnesota Power Ash	140 kg N ha^{-1} Bio +MN ash
8		Agricultural Lime	lime
9	x	urea @ 140 kg N ha^{-1}	N
10		Potash [c/]	K
11		urea @ 140 kg N ha^{-1} + Potash	N+K
12		urea @ 140 kg N ha^{-1} + Potash + Ag Lime	N+K+lime
13		Potlatch Cloquet Ash [d/]	Clq ash
14		Potlatch Cloquet Ash + urea @ 140 kg N ha^{-1}	Clq ash+N

[a/] All biosolids and urea rates were based on an X rate of 140 kg available N ha^{-1} (125 lb N ac^{-1}).
[b/] All lime and ash treatments were added to obtain a target soil pH of 6.0.
[c/] All potash (KCl) was applied at the MN Power application rate of K, or 234.2 kg K_2O ha^{-1} (209.1 lb K_2O ac^{-1}).
[d/] Potlatch ash treatments 13 and 14 are at the Carlton County (Cloquet) site only.

In Minnesota, where acidic agricultural soils are commonly amended with lime or ash, liming materials are analyzed and distinguished from one another on the basis of Effective Neutralizing Power (ENP). See Appendix A for detailed calculations of ENP, which is based on the calcium carbonate equivalent (CCE) and particle size (Rosen and Eliason 1996). Ash and agricultural lime application rates were based on their respective measures of ENP. Boiler ash was obtained from the Minnesota Power Company in Duluth and Potlatch Wood Products in Cloquet. Ash from Minnesota Power (ENP=21.8%) is derived from coal, Lake Superior Paper Industries

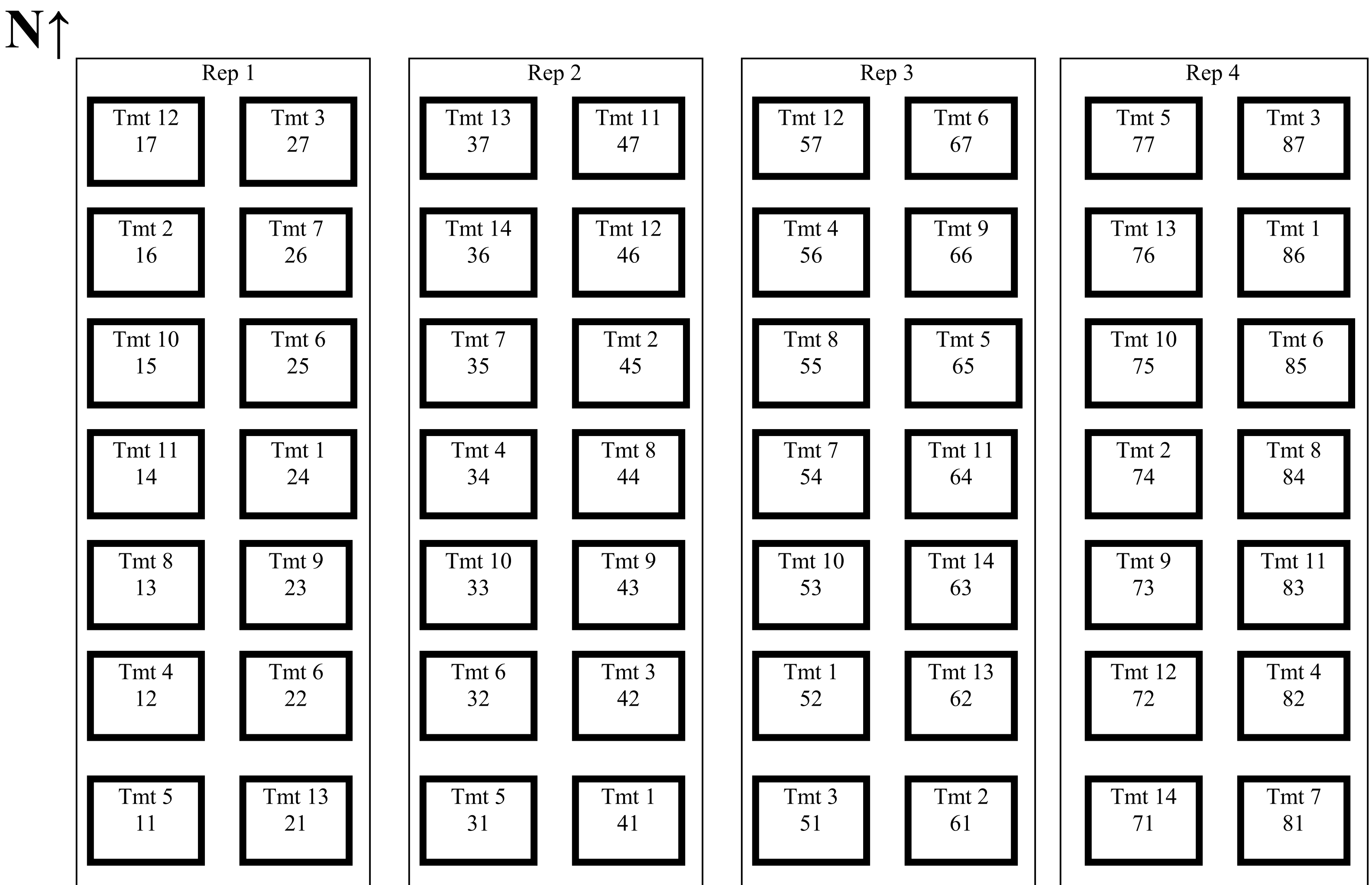

Figure 1. Plot layout at the Carlton County field site at the Cloquet Forestry Center, each plot with treatment ID (1st number) and plot ID (2nd number). For key to treatment numbers see Table 3.

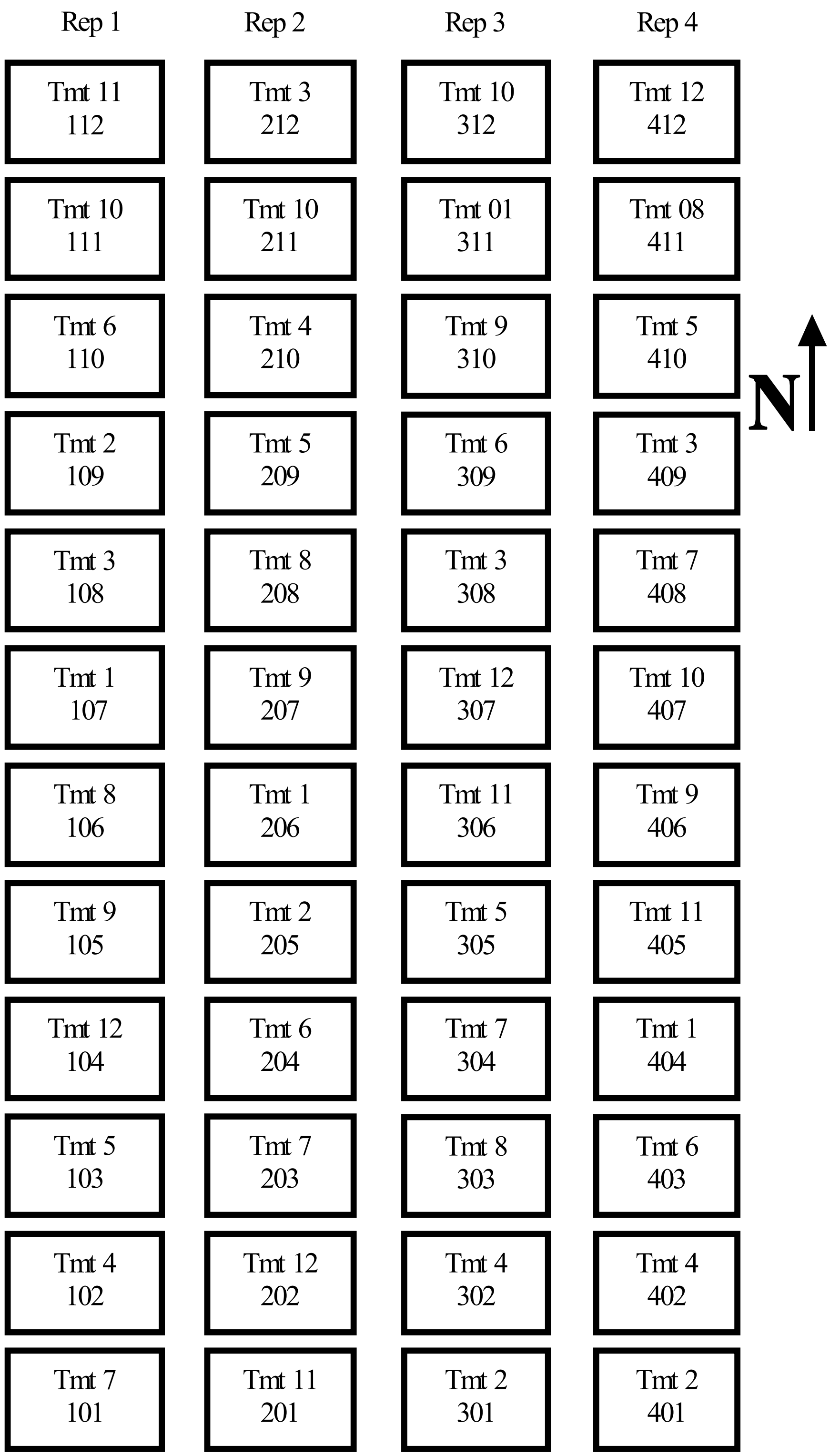

Figure 2. Plot layout at the Itasca County field site at the Grand Rapids North Central Research and Outreach Center, each plot with treatment ID (1^{st} number) and plot ID (2^{nd} number). For key to treatment numbers see Table 3.

wood, purchased wood, and railroad tie chips. Potlatch Cloquet ash (ENP=36.8) is derived from burning wood bark, sawdust, non-recyclable paper, cardboard, rejected knots from pulping operation, primary paper mill sludge[1], and coal. In treatments 6, 7, 13, and 14 (Table 3) ash was applied at a liming rate equivalent based on raising the soil pH to a target of 6.0 (Rosen and Eliason 1996). The pretreatment Carlton soil pH was 5.1, while the Itasca pH was 5.7 (Table 1). Carlton County soil was more acidic, so lime and ash were applied at greater rates than at the Itasca County site.

Anaerobically digested biosolids from Grand Chute Menasha Water Treatment Plant (GCMWTP) in Winnebago County, Wisc., were used instead of biosolids locally produced through the Western Lake Superior Sanitary District (WLSSD) because WLSSD used a lime stabilization process in 2000, but has since converted to an anaerobically digesting process similar to that used in Menasha. Wisconsin biosolids contained 13.88 kg of available N per metric ton of biosolids and were 19.5% dry matter. Biosolids treatments 2, 3, 4, 5, and 7 (Table 3) were all variations on a base application rate of 140 kg available N ha^{-1}, or 1.0X. This rate was used to keep the maximum rate 280 kg available N ha^{-1}, or 2.0X, from exceeding the recommended maximum application rate of nitrogen (250 kg total N ha^{-1}) contained in biosolids gleaned from the literature (Wells et al. 1986; Riddell-Black 1998; Matysik et al. 2001).

Experimental Treatments: Inorganic Fertilizers and Lime

In treatments 9, 11, 12, and 14 (Table 3) urea ($CO(NH_2)_2$) was applied at a base rate of 1.0X, or 140 kg available N ha^{-1} to supply inorganic nitrogen. In treatments 8 and 12 (Table 3) agricultural lime with an ENP of 70% was applied at a liming rate equivalent based on raising the soil pH to a target of 6.0. In treatments 10, 11, and 12 potash was applied based on rates of K applied with the Minnesota Power ash treatments, or 234.2 kg K_2O ha^{-1}. See Appendix B for detailed rate calculations for all treatments.

Aspen Seedlings

Double-flushed containerized seedlings of native aspen (*Populus tremuloides* Michx.) originating from seed sources local to Grand Rapids, Minn., were planted in 83.61 m^2 plots in 25 tree blocks at a 1.52 m by 1.52 m spacing. Seedlings were planted in Itasca County on June 20 and 21, 2000, and in Carlton County on June 22, 2000. Plots were weeded by hand on two occasions to control competition from ground vegetation. The first weed removal in Itasca County was on July 5, 2000, and in Carlton County on July 6, 2000. Glyphosate was applied to the Itasca County site in early October following tree measurement when leaves that had not senesced were manually removed from the trees.

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[1]Primary papermill sludge contains approximately 50% organic cellulose fiber, and 50% inorganic coating chemicals such as clay, starch, and calcium carbonate.

Lysimeters

Suction lysimeters were installed on all plots containing treatments 1, 2, 3, 4, 5, and 9 (Table 3) to monitor nitrate leaching, soil water pH, and electrical conductivity. These treatments were: a no amendment control, the four rates of biosolids, and the treatment with only urea. Lysimeters were installed at a 36 inch depth in Itasca County on June 27, 2000, and a 32 inch depth in Carlton County on June 28, 2000. Differences in installation depths were due to differences in the depth to water table. Lysimeters were flushed in Itasca County on July 5, 2000, and in Carlton County on July 6, 2000, with their respective first collections being July 17 and July 20, 2000. Lysimeters were removed in May 2002.

Data Collection

Tree heights and survival were measured after the first growing season in 2000. Tree heights, survival, and caliper at 15 cm above the root collar were measured after the second growing season in 2001. In both years the seedlings were also assayed for deer browse and dieback. Composite soil surface (0-15 cm) samples were collected from all plots. Eight subsamples were collected from various locations within each plot, mixed and bagged. Composite subsurface (15-30 cm) samples were collected from the control plots, plots with the highest amounts of biosolids, ash plots, and ash/biosolids plots and mixed in the same fashion as described above. Samples from Itasca County were collected on September 28, 2000, and from Carlton County on September 26 and 27, 2000. The soil was then dried at 35°C (95°F) in a forced air dryer for three days, ground to pass through a 2 mm screen, and prepared for chemical analysis. Soil pH and buffer pH were measured in water (1:1 w/w soil:water) (Thomas 1996). Soil was extracted with 1N ammonium acetate and exchangeable K was determined by Inductively Coupled Plasma (ICP) (Sumner and Miller 1996). Extractable P was measured by the Bray method (Kuo 1996).

Data Analysis

An arcsine transformation was used on percent survival data prior to an analysis of variance (ANOVA) to test the hypothesis of equal tree survival among treatments at each site (SPSS, Inc. 2000. SYSTAT 10.0. SPSS Inc., Chicago). Soil pH, P, and K, in 2000; aspen height data in 2000; and aspen height and caliper data in 2001 were all analyzed using ANOVA procedures in the JMP software package (JMP, Version 4. SAS Institute Inc., Cary, NC, 1989-2000). Fisher's least significant difference (LSD) mean comparison procedures were used to evaluate treatment effects.

Results and Discussion

Seedling survival was high in both sites, and by the end of the second growing season there was 89% survival of the planted seedlings at Carlton and 88% survival at Itasca (Table 4). No significant differences were detected in aspen seedling survival among treatments at the conclusion of the 2000 or 2001 growing seasons at either installation (Table 4). A high percentage of aspen seedlings were browsed by deer, and the percentages on both sites remained fairly constant for both growing seasons (Table 4). This is not expected to affect future survival due to the rapid growth of aspen. The percentages of plants exhibiting tip dieback increased slightly from one growing season to the next on both sites (Table 4). The causes of tip dieback were difficult to discern. Some possible causes of dieback could have been defoliation from the forest tent caterpillar (*Malacosoma disstria* Hbn.), or morning cloak butterfly (*Nymphalis antiopa*), which were both at high population levels in 2000 and 2001. Other damaging agents could have been aspen twig blight (*Venturia tremulae*), or frost.

Table 4. Percentage of plants with deer browse, percentage of plants exhibiting tip dieback, percent survival of planted seedlings, and p-values for analyses of variance testing the hypothesis of equal percent survival among treatments for both sites at the end of the 2000 and the 2001 growing seasons.

Site	**Carlton County**		**Itasca County**	
Growing Season	**2000**	**2001**	**2000**	**2001**
% Deer Browse	74 %	57 %	66 %	68 %
% Tip Dieback	6 %	23 %	16 %	24 %
% Survival	96 %	89 %	98 %	88 %
P-value H_0: % survival equal among treatments	0.664	0.152	0.549	0.514

All selected soil properties were affected by treatments in both surface and subsurface soil samples (Tables 5 and 6). Surface soil pH decreased with increased N application from both biosolids and fertilizer sources, but increased through additions of boiler ash and lime. Surface soil P increased with increased biosolids and ash application rates. Surface soil K increased with ash and K fertilizer applications. No change in subsurface soil P was observed. Subsurface soil K increased following K fertilizer addition at the Carlton County site but was not affected at the Itasca County site. This is likely due to the coarser soil texture at the Carlton County site.

Height differences among treatments were detected through ANOVA in 2000 and 2001 (Table 7), but interpretation of growth data for first growing season is difficult because the greenhouse environment in which the containerized seedlings were grown affected their first year vigor. Their rooting environment was also affected by the soil contained in the root plug at the time of planting. Differences in height growth that can be attributed to treatments will become increasingly evident over time. There was a site effect on both height and caliper growth, however (Table 8). Heights in 2000 and both height and caliper measurements in 2001 were greater at the Carlton County site than at the Itasca County site (Figs. 3-5).

There is considerable variation in the water quality data collected from the lysimeters (Figures 6 through 11) making interpretation difficult. Nitrate levels were lower in the untreated control plots during both years of monitoring in both Carlton and Itasca counties (Figures 6 and 7). Electrical conductivity remained relatively constant for all treatments in Carlton County in 2001 (Figure 8). Electrical conductivity was relatively constant for all treatments except the 1.0X biosolid treatment and 1.0X ammonium nitrate treatment in Itasca County in 2001 (Figure 9). Soil pH showed an increasing trend for all treatments in Carlton County but a decreasing trend for all treatment in Itasca County in 2001 (Figures 10 and 11).

Table 5. Effect of fertilizers, lime, and by-products on selected surface soil (0−15 cm depth) characteristics (pH, P, K) for each treatment per installation site in September 2000. Treatment means are displayed.

ID	Treatment	Carlton County Surface Soil Characteristics				Itasca County Surface Soil Characteristics			
		n	pH	P	K	n	pH	P	K
				---- mg kg^{-1} ----				---- mg kg^{-1} -----	
1	Ctrl	4	5.03	56.8	68.8	4	5.60	81.3	124.8
2	70 kg N ha^{-1} Bio	4	4.63	63.3	69.5	4	5.58	76.3	120.3
3	140 kg N ha^{-1} Bio	4	4.70	66.0	64.3	4	5.20	78.5	115.0
4	210 kg N ha^{-1} Bio	4	4.63	57.5	72.8	4	5.20	98.8	94.8
5	240 kg N ha^{-1} Bio	4	4.58	71.5	69.0	4	5.38	88.0	114.5
6	MN ash	5	5.82	66.4	151.8	4	6.18	81.0	171.0
7	140 kg N ha^{-1} Bio +MN ash	4	5.60	64.3	131.0	4	5.70	110.3	147.3
8	Lime	4	6.03	55.5	77.3	4	6.18	74.8	103.5
9	N	4	4.68	63.3	69.3	4	5.18	93.3	108.0
10	K	4	4.75	53.5	189.0	4	5.48	57.0	176.3
11	N+K	4	4.55	54.8	149.0	4	5.13	73.0	194.3
12	N+K+lime	4	5.20	52.5	157.3	4	5.55	73.5	169.5
13	Clq ash	4	5.00	68.5	99.8				
14	Clq ash+N	3	4.83	58.3	89.3				
	significance[a/]		***	ns	***		***	*	***
	LSD (ρ=0.05) [b/]		0.44		33.0		0.43	26.3	39.0

[a/] *, **, *** Significant differences at the 0.05, 0.01, 0.001 probability levels, respectively.
[b/] Fisher's Least Significant Difference at the 0.05 level.

Table 6. Effect of fertilizers, lime, and by-products on selected subsurface soil (15-30 cm depth) characteristics (pH, P, K) for each treatment per installation site in September 2000. Treatment means are displayed.

ID	Treatment	Carlton County				Itasca County			
		n	pH	P	K	n	pH	P	K
				-- mg kg^{-1} --				-- mg kg^{-1} --	
1	Control	4	5.23	54.3	49.0	4	5.53	67.0	59.8
5	240 kg N ha^{-1} Biosolids	4	4.83	48.5	46.3	4	5.23	69.8	59.3
6	MN Power ash	4	5.20	62.8	88.3	4	5.53	70.0	62.0
7	140 kg N ha^{-1} Biosolids +MN Power ash	4	4.95	59.8	61.8	4	5.45	77.5	63.5
13	Cloquet ash	4	5.20	60.8	44.0				
	significance[a/]		***	ns	**		**	ns	ns
	LSD (ρ=0.05) [b/]		0.15		20.5		0.20		

[a/] *, **, *** Significant differences at the 0.05, 0.01, 0.001 probability levels, respectively.
[b/] Fisher's Least Significant Difference at the 0.05 level.

Table 7. Effect of fertilizers, lime, and by-products on height growth in 2000 and height and caliper (at 15 cm from root collar) growth in 2001 for each treatment per installation site. Treatment means are displayed.

ID	Treatment	Carlton County					Itasca County				
		-- 2000 --		---------- 2001 ----------			-- 2000 --		---------- 2001 ----------		
		n	Height cm	n	Height cm	Caliper mm	n	Height cm	n	Height cm	Caliper mm
1	Ctrl	97	32.6	91	44.9	4.76	99	32.3	94	36.9	3.54
2	70 kg N ha^{-1} Bio	97	33.8	91	45.1	4.90	95	30.9	84	38.8	3.75
3	140 kg N ha^{-1} Bio	96	33.4	88	40.1	4.49	99	30.1	83	36.9	3.67
4	210 kg N ha^{-1} Bio	97	36.0	92	45.4	4.89	95	27.6	84	34.5	3.72
5	240 kg N ha^{-1} Bio	92	32.8	81	40.9	4.37	99	30.9	89	38.0	3.97
6	MN ash	120	33.4	110	41.2	4.51	99	32.2	95	35.6	3.44
7	140 kg N ha^{-1} Bio +MN ash	94	32.4	83	40.5	4.58	95	31.2	82	37.2	3.76
8	Lime	97	36.3	95	45.1	4.91	97	29.8	90	36.1	3.38
9	N	97	32.3	93	42.0	4.39	98	31.1	90	36.5	3.52
10	K	99	34.6	89	43.4	4.76	97	30.2	84	36.2	3.37
11	N+K	94	34.4	93	41.6	4.56	98	30.8	86	36.3	3.54
12	N+K+lime	93	33.4	85	43.7	4.72	98	29.6	92	35.5	3.34
13	Clq ash	96	33.6	87	41.0	4.25					
14	Clq ash+N	72	32.9	73[a/]	42.3	4.63					
	significance[b/]		*		*	**		**		ns	***
	LSD (ρ=0.05) [c/]		2.4		3.6	0.40		2.1			0.27

[a/] n is larger in year 2001 than 2000 because of new sprouting.
[b/] *, **, *** Significant differences at the 0.05, 0.01, 0.001 probability levels, respectively.
[c/] Fisher's Least Significant Difference at the 0.05 level.

Table 8. Means and standard errors in parentheses of aspen height and caliper data for all treatments combined in Carlton County and Itasca County.

	Height in 2000 -- cm --	Height in 2001 -- cm --	Caliper at 15 cm from the root collar in 2001 -- mm --
Carlton County	33.7 (0.2)	42.9 (0.4)	4.63 (0.04)
Itasca County	30.6 (0.2)	36.5 (0.3)	3.58 (0.03)

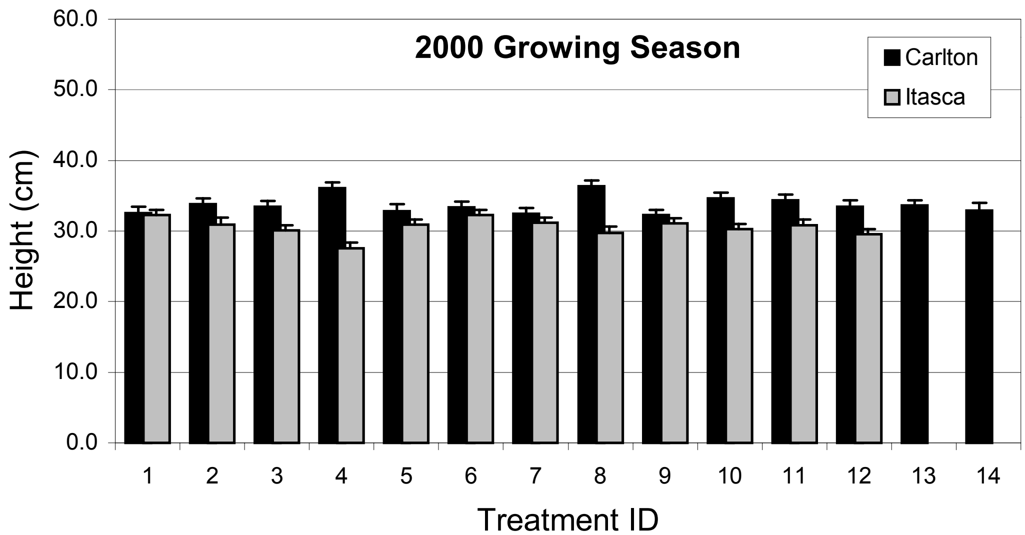


Figure 3. Mean aspen height in cm (and standard error bars) at the end of the 2000 growing season at both installation sites for all treatments. Note that treatments 13 and 14 were installed in the Carlton site only. See Table 3 for treatment descriptions.

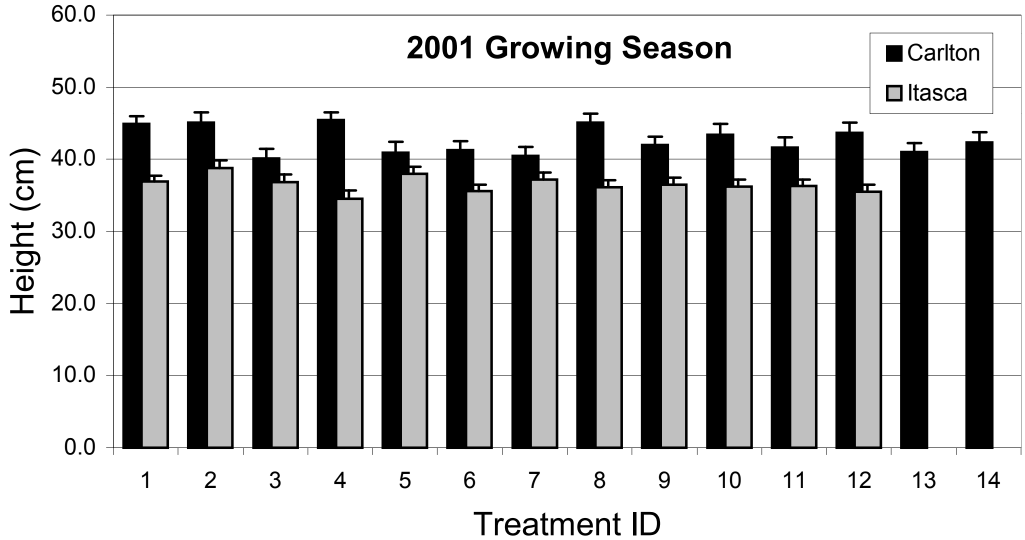


Figure 4. Mean aspen height in cm (and standard error bars) at the end of the 2001 growing season at both installation sites for all treatments. Note that treatments 13 and 14 were installed in the Carlton site only. See Table 3 for treatment descriptions.

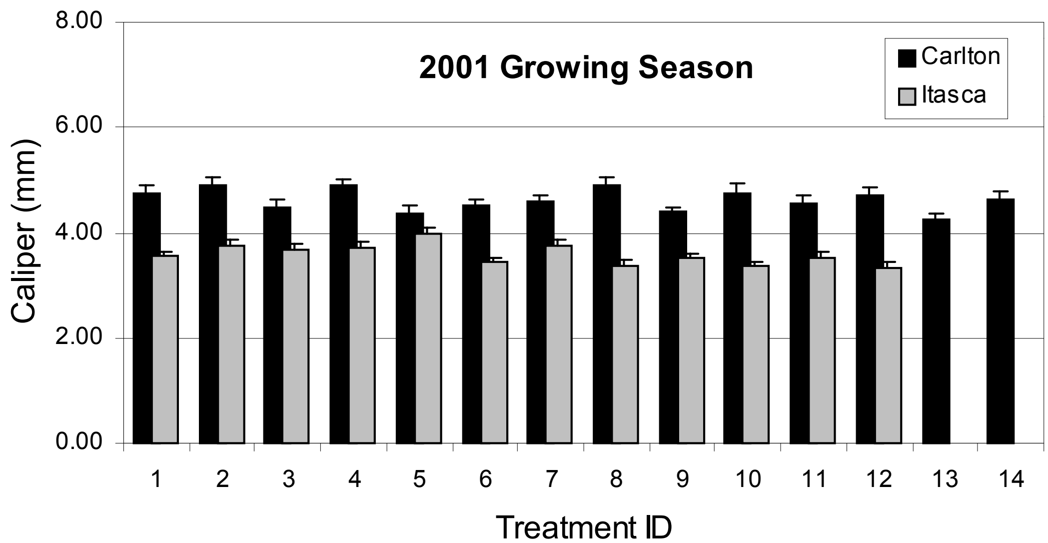
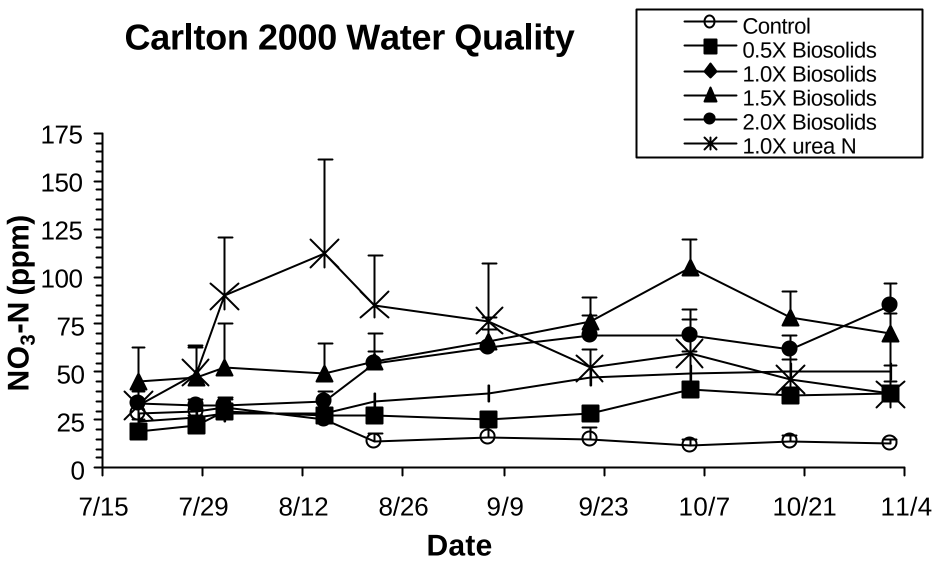


Figure 5. Mean aspen caliper in mm at 15 cm from the root collar (and standard error bars) at the end of the 2001 growing season at both installation sites for all treatments. Note that treatments 13 and 14 were installed in the Carlton site only. See Table 3 for treatment descriptions.



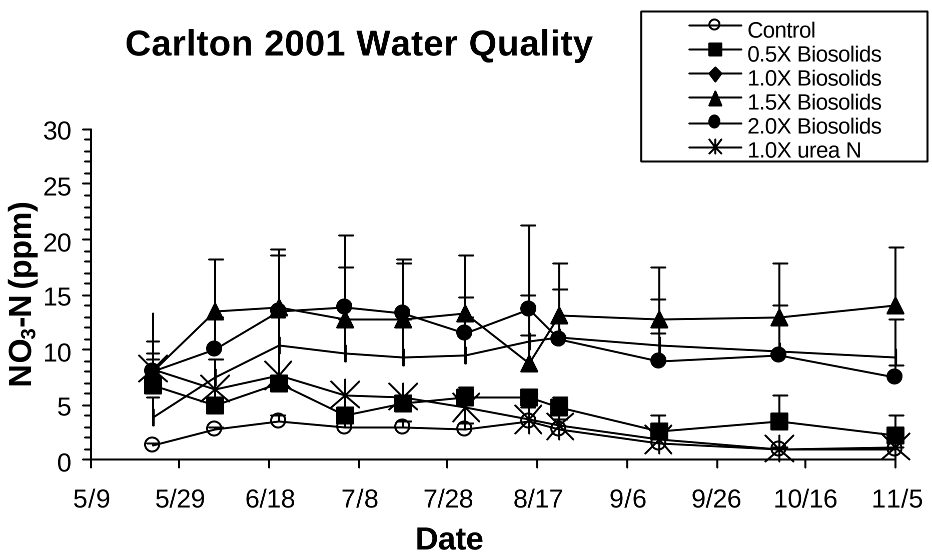
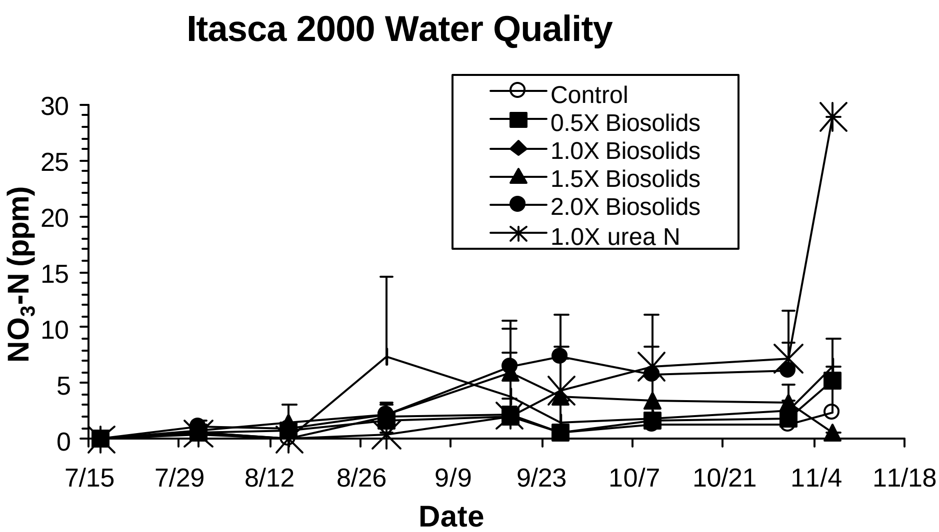


Figure 6. Mean concentration of NO_3-N (ppm) in soil water extracted from lysimeters (and standard error bars) at the Cloquet, Carlton County site in 2000 and 2001. All urea and biosolids rates were based on an "X" rate of 140 kg available N ha^{-1}.



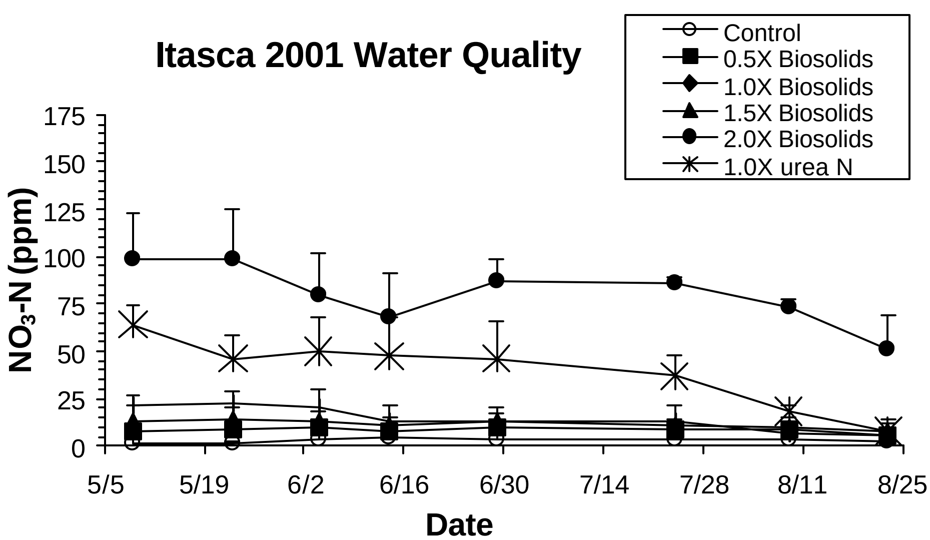


Figure 7. Mean concentration of NO_3-N (ppm) in soil water extracted from lysimeters (and standard error bars) at the Grand Rapids, Itasca County site in 2000 and 2001. All urea and biosolids rates were based on an "X" rate of 140 kg available N ha^{-1}.

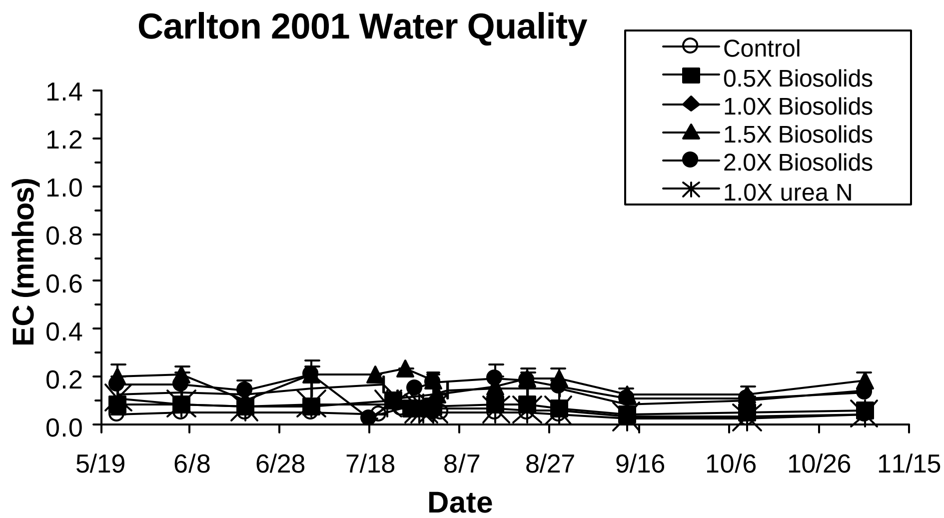


Figure 8. Mean Electrical Conductivity, EC, (mmhos) in soil water extracted from lysimeters (and standard error bars) at the Cloquet, Carlton County site in 2001. All urea and biosolids rates were based on an "X" rate of 140 kg available N ha^{-1}.

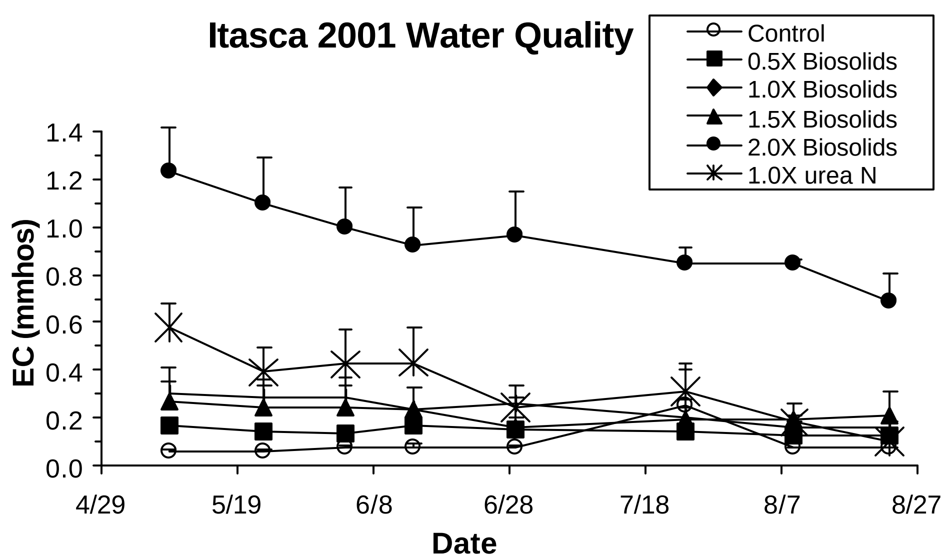


Figure 9. Mean Electrical Conductivity, EC, (mmhos) in soil water extracted from lysimeters (and standard error bars) at the Grand Rapids, Itasca County site in 2001. All urea and biosolids rates were based on an "X" rate of 140 kg available N ha^{-1}.

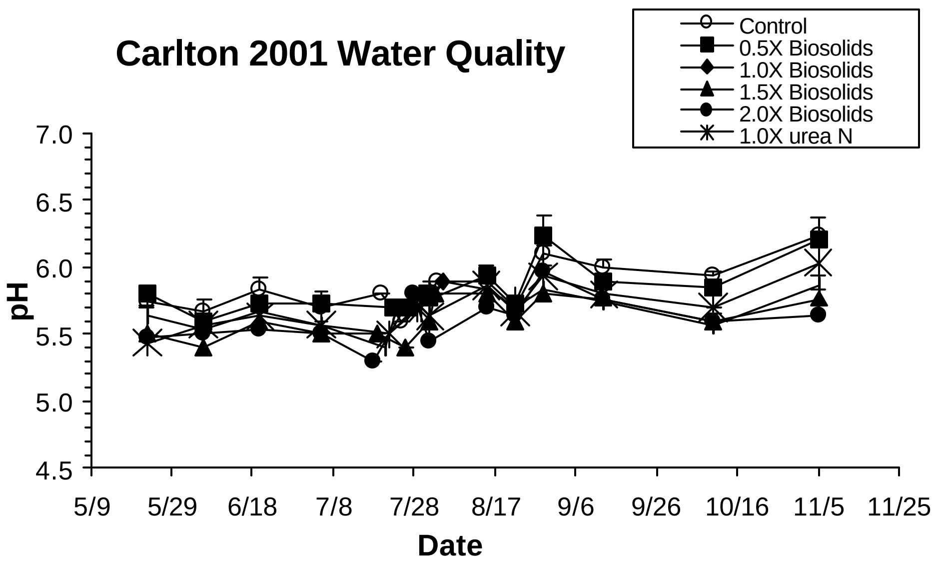


Figure 10. Mean pH in soil water extracted from lysimeters (and standard error bars) at the Cloquet, Carlton County site in 2001. All urea and biosolids rates were based on an "X" rate of 140 kg available N ha^{-1}.

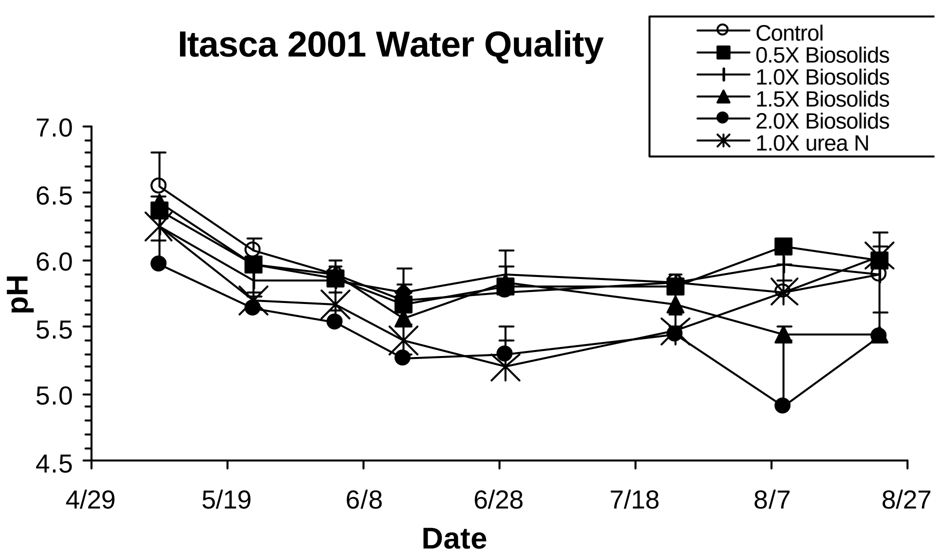


Figure 11. Mean pH in soil water extracted from lysimeters (and standard error bars) at the Grand Rapids, Itasca County site in 2001. All urea and biosolids rates were based on an "X" rate of 140 kg available N ha^{-1}.

Literature Cited

Johnson, F. J. 1990a. Agricultural liming materials. In *Official methods of analysis of the Association of Official Analytical Chemists*, ed., Helrich, K., 955.01, 15th ed. Arlington, VA: AOAC.

Johnson, F. J. 1990b. Fertilizers. In *Official methods of analysis of the Association of Official Analytical Chemists*, ed., Helrich, K., 960.02, 963.03, 978.01, 15th ed. Arlington, VA: AOAC.

Kuo, S. 1996. Phosphorus. In *Methods of soil analysis, Part 3: Chemical methods*, ed., Sparks, D. L., 869-919. Madison, WI: SSSA.

Matysik, M. A., D. W. Gilmore, M. Mozaffari, C. J. Rosen, and T. R. Halbach. 2001. *Application of wood ash, biosolids, and paper mill sludge amendments to forest soils—a review of the literature.* Staff Paper Series no. 153. St. Paul, MN: Department of Forest Resources, University of Minnesota. 18 p.

Riddell-Black, D. 1998. Development of a water industry manual for biosolids use in short rotation forestry. *Biomass Bioenerg*. 15:101-107.

Rosen, C. J., and R. Eliason. 1996. *Nutrient management for commercial fruit and vegetable crops in Minnesota.* St. Paul, MN: Minnesota Extension Service, University of Minnesota College of Agricultural, Food and Environmental Sciences.

Sumner, M. E., and W. P. Miller. 1996. Cation exchange capacity, and exchange coefficients. In *Methods of soil analysis. Part 2: Chemical Properties*, ed., Sparks, D. L. 3d ed. Madison, WI: ASA, SSA, CSSA.

Thomas, G. W. 1996. Soil pH and soil acidity. In *Methods of soil analysis. Part 3: Chemical Methods,* ed. Sparks, D. L., 475-490. Madison, WI: ASA, SSSA.

U.S. Environmental Protection Agency. 1992. Test method for evaluating solid waste. *Physical/chemical methods*, 3d ed. Washington, D.C.: USEPA, Office of Solid Waste and Emergency Response.

Wells, C. G., C. E. Murphy, C. Davis, D. M. Stone, and G. J. Hollod. 1986. Effect of sewage sludge from two sources on element flux in soil solution of loblolly pine plantations. In *The forest alternative for treatment and utilization of municipal and industrial wastes,* eds., Cole, D. W., C. L. Henry, and W. L. Nutter. Seattle, WA: University of Washington Press.

APPENDIX A: Effective Neutralizing Power Calculations

How ENP is calculated:

% ENP = % CCE x FI x % Dry Matter

CCE = Calcium Carbonate Equivalent. The amount of calcium/magnesium carbonate or calcium/magnesium oxide contained in the liming material. CCE is expressed as a percentage of 100% PURE calcium carbonate. Pure calcium carbonate is the standard by which all liming material chemical purity is compared.

FI = Finess Index. Determined in the laboratory by measuring the percentage of the liming material that passes through sieves of various sizes. Three sieve sizes (8 mesh, 20 mesh, 60 mesh) are used. The FI is determined from the following equation:

FI = (% passing 8 mesh but remaining on 20 mesh) x .2

+ (% passing 20 mesh but remaining on 60 mesh) x .6 + (% passing 60 mesh) x 1.0

APPENDIX B: Field Installation Treatment Calculations

Minnesota Power Ash: Treatments 6 and 7

Carlton County

Based on pretreatment buffer pH of 6.3 and a 22% ENP of the by-product, a liming rate of 3500 lb ac^{-1} is required to raise soil pH to 6.0

(3500 lb ENP ac^{-1}) / (22% ENP) = 15909 lb ash ac^{-1}

(15909 lb ash ac^{-1}) / (43560 ft^2 ac^{-1}) = 0.365 lb ash ft^2

(0.365 lb ash ft^{-2}) * (900 ft^2/plot) = 329 lb ash $plot^{-1}$

Itasca County

Based on pre-treatment buffer pH of 6.6 and a 22% ENP of the by-product, a liming rate of 2000 lb ac^{-1} is required to raise soil pH to 6.0

(2000 lb ENP ac^{-1}) / (22% ENP) = 9091 lb ash ac^{-1}

(9091 lb ash ac^{-1}) / (43560 ft^2 ac^{-1}) = 0.209 lb ash ft^2

(0.209 lb ash ft^{-2}) * (900 ft^2/plot) = 188 lb ash $plot^{-1}$

Biosolid Treatments: 2, 3, 4, 5, and 7

19.5% dry matter, 31.1 lb N dry ton^{-1}

N application rate X = 125 lb available N ac^{-1}

(125 lb N ac^{-1}) / (31.1 lb N dry ton^{-1}) = 4.02 dry ton ac^{-1}

(4.02 dry ton ac^{-1}) / (19.5% dry matter) = 20.61 ton ac^{-1}

(20.61 ton ac^{-1}) * (2000 lb ton^{-1}) / (43560 ft^2 ac^{-1}) = 0.946 lb ft^{-2}

(.946 lb ft^{-2}) * (900 ft^2 $plot^{-1}$) = 852 lb $plot^{-1}$

Treatment 2: (0.5X) = (.05) * (852 lb $plot^{-1}$) = 426 lb $plot^{-1}$

Treatment 3: (1.0X) = (1.0) * (852 lb $plot^{-1}$) = 852 lb $plot^{-1}$

Treatment 4: (1.5X) = (1.5) * (852 lb $plot^{-1}$) = 1278 lb $plot^{-1}$

Treatment 5: (2.0X) = (2.0) * (852 lb $plot^{-1}$) = 1704 lb $plot^{-1}$

note: In Carlton County there are 5 reps of Treatment 5

Agriculture Lime: Treatments 8 and 12

Carlton County

Based on pre-treatment buffer pH of 6.3 and a 70% ENP of the agriculture lime, a liming rate of 3500 lb ac^{-1} is required to raise soil pH to 6.0

(3500 lb ENP ac^{-1}) / (70% ENP) = 5000 lb lime ac^{-1}

(5000 lb lime ac^{-1}) / (43560 ft^2 ac^{-1}) = 0.1149 lb lime ft^{-2}

(0.1149 lb lime ft^{-2}) * (900 ft^2 $plot^{-1}$) = 103 lb lime $plot^{-1}$

Itasca County

Based on pre-treatment buffer pH of 6.6 and a 70% ENP of the agriculture lime, a liming rate of 2000 lb ac^{-1} is required to raise soil pH to 6.0.
(2000 lb ENP ac^{-1}) / (70% ENP) = 2857.1 lb lime ac^{-1}
(2857.1 lb lime ac^{-1}) / (43560 ft^2 ac^{-1}) = 0.0656 lb lime ft^{-2}
(0.0656 lb lime ft^{-2}) * (900 ft^2 $plot^{-1}$) = 59 lb lime $plot^{-1}$

Urea: Treatments 9, 11, and 12

N application rate X = 125 lb available N ac^{-1}; urea available N = 46%
(125 lb N ac^{-1}) / (31.1 lb N dry ton^{-1}) = 4.02 dry ton ac^{-1}
(125 lb N ac^{-1}) / (46% N) = 271.7 lb urea ac^{-1}
(271.7 lb urea ac^{-1}) / (43560 ft^2 ac^{-1}) = .00624 lb urea ft^{-2}
(0.00624 lb urea ft^{-2}) * (900 ft^2 $plot^{-1}$) = 5.6 lb urea $plot^{-1}$

Potash: Treatments 10, 11, 12

Carlton County
Based on Minnesota Power Ash K level of potash = 60% K_2O, and ash = 2.3% K_2O.
Calculation of K supplied in Treatment 6 from 15909 lb ash ac^{-1}
(15909 lb ash ac^{-1}) * (2.3% K_2O) = 365.9 lb K_2O ac^{-1}
(365.9 lb K2O ac^{-1}) / (60% K_2O) = 609.8 lb potash ac^{-1}
(609.8 lb potash ac^{-1}) / (43560 ft^2 ac^{-1}) = 0.014 lb potash ft^{-2}
(0.014 lb potash ft^2) * (900 ft^2 $plot^{-1}$) = 12.6 lb potash $plot^{-1}$

Itasca County
Based on Minnesota Power Ash K level of potash = 60% K_2O, and ash = 2.3% K_2O.
Calculation of K supplied in Treatment 6 from 9091 lb ash ac^{-1}
(9091 lb ash ac^{-1}) * (2.3% K_2O) = 209.1 lb K_2O ac^{-1}
(209.1 lb K2O ac^{-1}) / (60% K_2O) = 348.5 lb potash ac^{-1}
(348.5 lb potash ac^{-1}) / (43560 ft^2 ac^{-1}) = 0.008 lb potash ft^{-2}
(0.008 lb potash ft^2) * (900 ft^2 $plot^{-1}$) = 7.2 lb potash $plot^{-1}$

Potlatch Cloquet Ash: Treatments 13 and 14

Carlton County only
Based on pre-treatment buffer pH of 6.3 and 82.5% ENP of the by-product, a liming rate of 3500 lb ac^{-1} is required to raise soil pH to 6.0
(3500 lb ENP ac^{-1}) / (82.5% ENP) = 4242 lb ash ac^{-1}
(4242 lb ash ac^{-1}) / (43560 ft^2/ac) = 0.10 lb ash ft^{-2}
(0.10 lb ash ft^{-2}) * (900 ft^2 $plot^{-1}$) = 90 lb ash $plot^{-1}$

note: There are only 3 reps of Treatment 14

Appendix C. 2000-2001 Field Log

5/4/00 Mechanical site prep of Grand Rapids forest site.

5/24/00 Lay-out and flag Cloquet forest site.

6/1/00 Lay-out and flag Grand Rapids forest site.

6/5-8/00 Apply biosolids treatments to forest plots in Cloquet and Grand Rapids.

6/20/00 Plant seedlings in Grand Rapids forest plot.

6/22/00 Plant seedlings in Cloquet forest plot.

7/5-10/00 Hand weed forest plots in Grand Rapids and Cloquet.

8/1/00 Water samples collected from Grand Rapids forest plots.

9/12/00 Water samples collected from Grand Rapids forest plots.

9/26/00 Water samples collected from Grand Rapids forest plots.

9/28/00 Collected soil samples from Grand Rapids forest plots.

10/3/00 Measure Grand Rapids forest plots.

10/10/00 Measure Cloquet forest plots.

10/11/00 Apply 2% solution of Round Up to the Grand Rapids forest plots with boom sprayer. A total of 28 gallons of mixture used.

10/31/00 Water samples collected from Grand Rapids forest plots.

11/7/00 Water samples collected from Grand Rapids forest plots.

5/2/01 Apply 11/2 % solution of Round Up to the Grand Rapids forest plots with backpack sprayer. A total of 6 gallons used.

5/10/01 Water samples collected from Grand Rapids forest plots.

5/23/01 Water samples collected from Grand Rapids forest plots.

6/4/01 Water samples collected from Grand Rapids forest plots.

6/14/01 Water samples collected from Grand Rapids forest plots.

6/25/01 Hand weed Grand Rapids forest plots.

7/11/01 Apply Fusilaide to Grand Rapids forest plots, spot spray, with backpack sprayer.

7/24/01 Water samples collected from Grand Rapids forest plots.

8/9/01 Water samples collected from Grand Rapids forest plots.

8/23/01 Water samples collected from Grand Rapids forest plots.

10/18/01 Water samples collected from Grand Rapids forest plots.

11/15/01 Measure trees in Grand Rapids forest plots.

12/6/01 Measure trees in Cloquet forest plots.