DETERMINING OPTIMAL SAWDUST / BIOSOLIDS MIXTURES TO MANAGE NITRATE LEACHING IN RECLAIMED DISTURBED SOILS[1]

by

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Abstract: Higher than agronomic rates of biosolids are often applied as a soil amendment for reclamation of drastically disturbed lands. However, at these rates, NO_3-N leaching can occur, especially during the first winter. Our objective was to determine the effects of adding a high C residue (sawdust) to biosolids on NO_3-N leaching potentials and associated biomass production. Treatments were applied to a re-graded athletic field area in October 1993 and included a fertilized control and mixtures of 90 Mg/ha biosolids with 0:1, 0.5:1, 1:1 and 2:1 ratios of sawdust to biosolids (S:B), giving C:N ratios of 9.4:1, 19:1, 28:1, and 45:1 respectively. Zero-tension lysimeters were used to collect root zone leachates. The plots were seeded with tall fescue *(Fescue arundinacea* Schreb.). Leachate NO_3-N concentrations were greatest during the first winter (93/94), with the 0:1 sawdust:biosolids (S:B) averaging > 20 mg/L, while the higher S:B ratios and control remained <10 mg/L. During the second winter of leaching (94/95), nitrate-N leachate levels decreased markedly relative to the first season, with all treatments averaging < 10 mg/L. Standing biomass collected in May and November of 1994 indicated that the highest rate of sawdust (2:1 S:B) suppressed growth relative to the other treatments. While this trend remained visually evident, standing biomass showed no significant treatment effects after subsequent growing seasons. The lower biomass production on the 2:1 S:B plots resulted in higher leachate volumes, probably due to lower evapotranspiration. This increased volume of leachate resulted in the 2:1 S:B treatment generating the highest total NO_3-N mass loss during the first year, but a total NO_3-N mass loss similar to the other S:B treatments over the duration of the study. Therefore, moderate additions of high C residues (0.5 - 1:1 S:B) can reduce net NO_3-N losses via enhanced immobilization, while still providing adequate nutrients for plant growth.

Additional Key Words: Revegetation, agronomic rate, C:N ratio.

Introduction

Municipal wastewater treatment biosolids have been shown to be a good substitute for chemical fertilizers when used for agriculture or reclamation. The biosolids enhance organic matter, nutrient pools, water holding capacity, and overall long-term soil productivity (Haering et al., 2000). Studies have also found that biosolids can produce a greater standing biomass than topsoil or chemical fertilizers on reclaimed mining sites (Roberts et al., 1988).

Applications of biosolids in conventional farm management scenarios are typically limited to only the amount of N needed by the subsequently grown crop. Higher than agronomic rates (ranging from 50 to > 200 Mg/ha) of biosolids are commonly applied in mined land reclamation scenarios (Sopper, 1993) under the assumption that NO_3-N losses to ground water will have minimal long-term negative effects from one-time application. Detailed research studies in Pennsylvania (Carello, 1990; Sopper and Seaker, 1990) and Virginia

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(Daniels and Haering, 1994) concluded that application of higher than agronomic rates of various biosolids products to coal mined lands had little, if any, short- or long-term effects on ground water NO_3-N levels under application areas or at permitted surface water discharge points. Significant NO_3-N leaching following heavy biosolids applications to forest lands on gravelly coarse-textured soils in the Pacific Northwest has been reported by Riekerk (1978, 1981), but the observed effects were ephemeral, largely limited to the first two winters after application.

A potential method for limiting nitrate leaching from biosolids application is to adjust the C:N ratio by mixing the biosolids with a high C compound such as sawdust (200-750 C:N). Nitrate should not leach as readily from biosolids mixtures with higher C content because, in addition to plant immobilization, heterotrophic bacteria immobilize inorganic N from the soil solution while they degrade the C substrate. Immobilization of nitrogen by microbes is increased dramatically through the addition of woody residues (Sabey et al., 1975, Parker and Sommers, 1983). A problem may exist, however, if there is too much high C material applied and the bacteria immobilize or denitrify the soil N, leading to N deficiency.

Previous research has been conducted concerning the use of digested sewage sludge mixed in varying ratios with wood wastes (Sabey et al., 1975; Agbim et al., 1975; Sabey et al., 1977). Laboratory experiments on N accumulation and CO_2 emission, and greenhouse experiments on the effect of these amendments on wheat growth were conducted. Both wood, bark and a mixture of the two were tested with 0 to 100 percent wood material/biosolids mixtures. The wood material was less than 9.5 mm, so its particle size was intermediate between experiments conducted using wood chips (Daniels and Haering, 1994) and the study reported herein using sawdust. Sabey et al. (1975, 1977) found C:N ratios between 10.3 and 18.0 to be the most effective for wheat growth. Strict use of the C:N ratio is limited due to the variability associated with the stability of the compounds, not just their total elemental content. This unpredictability is seen with the bark materials; that while having a lower C:N ratio than the wood material, bark caused net immobilization of nitrogen in 50:50 mixtures with biosolids, thereby causing nitrogen deficiencies and reduced growth in wheat (Sabey et al., 1977). The deficiencies and reduced growth were not observed in the 50:50 mixtures of biosolids and wood residue. Sabey et al. (1977) also observed high NO_3-N levels in the soil, especially in the higher percentage biosolids and higher application rate treatments, which raises the concern of ground-water contamination. The lack of field NO_3-N leaching data indicated the need for further research to determine the most effective mixture of wood waste and biosolids.

In this experiment, a range of sawdust addition mixture rates to a constant mass of biosoilds were evaluated to determine the optimum C:N ratio to prevent excessive nitrate leaching without inhibiting plant growth. Specific objectives were to compare effects of four sawdust:biosolids (S:B) ratios on (1) NO_3-N leaching potentials, and (2) standing biomass and soil properties.

Methods and Materials

The site for the study was a field on the campus of Thomas Jefferson High School for Science and Technology in Fairfax County, Virginia. The previously cut and graded area had not been used, watered, or recently fertilized as an athletic field; its only maintenance was occasional mowing. The soil was identified as a truncated Beltsville silt loam from its texture, color, a fragipan at approximately 40-cm, and the Fairfax County Virginia soil survey (1963). The Beltsville series, a Typic Fragiudult, consists of light-colored, somewhat poorly to well drained soils that developed from sand, silt and clay from the Coastal Plain. Permission to apply biosolids in a small plot experiment was approved by the Virginia Department of Health. The area was tilled several times with a rototiller to a depth of 20 to 30 cm prior to adding the soil amendments. Soil samples were taken and tested for macronutrients and pH to determine liming and fertilization requirements. Four Mg/ha of pelletized agricultural lime was added to the entire site on September 17, 1993 to raise the soil pH from its initial level of 4.9 to a target pH of 7.0.

The site was divided into 20 plots, each measuring 2 X 2 m. The plots were arranged in a randomized block design with four replications of five different amendment treatments, blocked to eliminate any effect of a shadow cast by adjacent athletic bleachers. Buffer strips measured 1 m between replications and 0.5 meter within replications. Zero tension lysimeters were placed 45 cm deep in the center of 15 of the plots (3 replications); their design is described in our companion paper (Daniels et al., 2001). Four different ratios of sawdust to biosolids (S:B) were chosen as amendments, along with a fertilized control. The anaerobically digested lime-stabilized municipal sewage sludge cake was obtained from the Alexandria, Virginia water treatment plant (see Table 1). The biosolids were applied at a rate consistent with disturbed land reclamation of 90 Mg/ha (dry) along

Table 1. Biosolids properties from Alexandria, Virginia water treatment plant on October 5, 1993.

Biosolids Properties/ Macronutrient (g/kg)		Micronutrient/Metal (mg/kg)	
Solids	286	Iron	103,600
Volatile Solids	343	Mercury	1.07
Carbon	218	Magnesium	2,300
Nitrogen (TKN)	23.1	Manganese	139
Ammonia N	2.8	Selenium	1.62
Nitrate N	0.99	Molybdenum	38
Organic N	18.9	Sodium	400
Phosphorus	16.6	Copper	200
Potassium	0.30	Zinc	380
Sulfur	10	Cadmium	< 0.5
pH (std. units)	12.10	Nickel	10
Ca Carb. Eq.	286	Calcium	178,000
		Lead	30
		Chromium	60

with sawdust in 0:1, 0.5:1, 1:1, and 2:1 (dry) sawdust to biosolids weight ratios. The biosolids and sawdust were mixed together before being placed on the plots. The white oak (*Quercus alba* L.) sawdust was obtained from a local sawmill and contained 48% solids. A 10-20-10 fertilizer was applied to the four control plots at a rate of 500 kg/ha. The soil amendments were then incorporated into the soil to a depth of between 20 and 30 cm with a rototiller. The site was fenced to limit access.

C:N ratios for each treatment can be calculated from the 9.4:1 C:N ratio for biosolids and the 354:1 C:N and 47.3% C content for sawdust. The C:N ratio of the sawdust:biosolids treatments as applied ranged from 9.4:1 for the 0:1 S:B, 19:1 for the 0.5:1 S:B, 28:1 for 1:1 S:B, and 45:1 for the 2:1 S:B. On October 6, 1993, Kentucky-31 tall fescue (*Fescue arundinacea* Schreb.) was seeded on the entire site at a rate of 28 g/m^2. To ensure cover by the onset of winter, winter rye was overseeded on the site at a rate of 3.4 g/m^2 on October 12.

Water samples were drawn from the lysimeters monthly. The water samples were tested for NO_3-N and pH with a Hach DR/2000 spectrophotometer and pH meter using the cadmium reduction method for NO_3-N. The samples were drawn with a hand pump into a clean flask and analyzed within 12 hours of sampling. The pump and apparatus were rinsed with deionized water between each sample. The samples were filtered through medium grade filter paper if there was a visible amount of suspended sediment. The high NO_3-N leaching levels during the second leaching season for one plot (1:1 S:B) adjacent to the fence suggest that this site was contaminated with urine during that growing season. Animal activity on the site, or the location of the site behind the football bleachers, may account for this contamination. For this reason, plot 10 was excluded from the mean NO_3-N levels and statistical analysis during the second leaching season.

Standing biomass was collected in spring 1994 and fall 1994, 1995, and 1996 from a random sub-sample of each plot measuring approximately 30 X 30 cm. The previous year's sampling location, the lysimeter position, and the fringes of the plots were excluded from sampling. The standing biomass was collected by hand clipping all material in the area to ground level. The samples were then oven dried at 60 °C until their weight was constant.

Soil samples were collected periodically to assess the possible accumulation of metals in the soil and the soil's nutrient status. Multiple random samples were collected with a hand core sampler from the upper 20 cm of the soil surface and then mixed together for each plot. After drying, the samples were passed through a 2-mm sieve. Samples were analyzed for C using a Leco furnace and for N by the Kjeldahl procedure. Other nutrients reported were analyzed by the Virginia Tech Soil Testing Lab via dilute double acid (Mehlich III) extraction followed by ICPES (Donohue and Heckendorn, 1994).

All statistical comparisons were conducted using SAS version 7-1 using the "glm" procedure to conduct ANOVAs followed by LSD mean separations. Typically, $p \leq 0.05$ was used to determine whether results were significant, although considering the low sample size and variability of some results, a level of $p = 0.10$ was also used to indicate trends.

Results and Discussion

Plant Growth

The standing biomass results (Table 2) exhibited differences only in May and November of 1994. The standing biomass yields of the 2:1 sawdust:biosolids treatment were consistently low, suggesting the high C:N ratio (45:1) limited plant growth due to N immobilization. While the fertilized control exhibited similar plant yields to the 0:1 and 1:1 S:B treatments at the beginning of the first growing season, by fall 1994 both of these treatments produced higher yields than the fertilized control (Table 2). While there were no significant differences ($p \leq 0.05$) among treatments after the second and third growing seasons, the trend

Table 2. Standing biomass yield (Mg/ha) for each sawdust:biosolids (S:B) treatment and the fertilized control for May 1994, November 1994, November 1995 and December 1996.

Date:	May-94	Nov-94	Nov-95	Dec-96
Treatment	Standing Biomass (Mg/ha)			
0:1 S:B	3.17ab*	6.30a	5.34a	8.00a
0.5:1 S:B	2.28bc	5.51ab	4.45a	7.89a
1:1 S:B	2.79ab	6.31a	4.58a	7.50a
2:1 S:B	0.95c	3.85c	4.24a	6.85a
Fert. Control	3.82a	4.35bc	4.58a	5.85a

* Values followed by the same letter with the same sampling date are not significantly different at p = 0.05 level.

Table 3. Percent total soil C and N for sawdust:biosolids ratios and fertilized control treatments in November 1994.

Treatment	Soil Content		
	% TC	% TN	C:N Ratio
0:1 S:B	6.8bc*	0.52a**	13.2b**
0.5:1 S:B	6.4bc	0.44ab	14.5b
1:1 S:B	8.4ab	0.56a	14.9ab
2:1 S:B	9.9a	0.55a	18.0a
Fert. Control	5.0c	0.34b	14.8ab

*, ** Values with the same letter in a column are not significantly different at p = 0.05 and p = 0.10 level respectively.

indicated higher yields on the biosolids amended soils, decreasing slightly with increasing amounts of sawdust. By December 1996, the 2:1 S:B treatment had even surpassed the fertilized control. This pattern of fewer significant differences as time goes on is similar to results reported later for leachate characteristics.

Soil Properties

In general, soil nutrient and metal concentrations followed those found in the biosolids and sawdust materials. Elements that typically occur in biosolids, such as Ca, N and some metals exhibited enriched soil content. Similarly, higher rates of sawdust produced higher soil C levels. Total soil C present after one year corresponded directly with the amount of organic material added to each treatment (Table 3). The sawdust and biosolids treatments soil C levels tended to be higher than the biosolids only and the fertilized control due to the high C content and C:N ratio of sawdust. After a year of leaching and plant and microbial uptake, the N levels in soil were higher than the fertilized control in three of four biosolids treatments (Table 3). This effect is likely due to the much higher organic-N mass loadings from the biosolids, which also takes longer to mineralize and leach. The soil C:N ratio is consistent with that of the amendments applied, exhibiting the characteristic increase from 0:1 to 2:1 S:B (Table 3).

Soil pH remained above 6.5 for all treatments during the study, keeping metals predominately in insoluble forms. This result suggests that any treatment effects on plant growth were due to differential nutrient levels or other soil properties. The fertilized control pH was less than all the biosolids treated plots (Table 4). The higher soil pH associated with biosolids application was consistent with the high pH and calcium carbonate equivalent of the lime stabilized biosolids (Tables 1 & 4). The significantly lower leachate pH values compared with measured soil pH presumably reflect active microbial process and relatively unbuffered macropore waters sampled by the zero-tension lysimeters as opposed to the bulk pH of the ground soil samples. The leachate pH exhibited a similar treatment pattern to the soil pH; with lower pH in the fertilized control than the treatments with sawdust and biosolids during the third and fourth seasons (Table 4). The lime that was added to the site prior to establishment may have masked the pH differences during the first two seasons. When examining the general trend and the results from the third season (95/96), it appears that the plots with sawdust and biosolids have a higher pH than those with biosolids alone (Table 4). It is unclear whether the sawdust had a pH buffering capacity or if the interaction between the sawdust, biosolids, and microbes is responsible.

Considering the relatively low levels of K in biosolids and sawdust, it is not surprising that K shows few differences between treatments (Table 5). The soil K levels are likely due to the background soil levels, although overall extractable K decreased between 1994 and 1997 suggesting some leaching or plant uptake losses. Soil Ca was enriched in the biosolids amended treatments throughout the experiment (Table 5). Calcium was clearly elevated for the lime-stabilized biosolids treatments by its' high Ca levels; over 17% on a dry weight basis. These high Ca levels may help account for the relatively high pH in the soil, assuming much of the Ca was in carbonate forms. Soil Mg

Table 4. Soil and leachate pH during each leaching period for each treatment.

Date	Treatment	Leachate pH	Soil pH
10/93-5/94	0:1 S:B	5.39a*	7.15a
	0.5:1 S:B	5.72a	7.18a
	1:1 S:B	6.3a	7.08a
	2:1 S:B	5.86a	7.15a
	Fert. Control	5.45a	6.52b
9/94-5/95	0:1 S:B	4.77a	
	0.5:1 S:B	5.11a	
	1:1 S:B	5.09a	
	2:1 S:B	5.19a	
	Fert. Control	4.98a	
9/95-5/96	0:1 S:B	4.66c	7.30ab
	0.5:1 S:B	5.21ab	7.35a
	1:1 S:B	5.46a	7.20b
	2:1 S:B	5.32ab	7.18b
	Fert. Control	4.82bc	6.75c
9/96-5/97	0:1 S:B	4.88abc	7.47a
	0.5:1 S:B	4.83bc	7.40a
	1:1 S:B	5.42a	7.37a
	2:1 S:B	5.2ab	7.40a
	Fert. Control	4.46c	6.80b

* Values followed by the same letter within the same date and column are not significantly different at p = 0.05 level.

exhibited the opposite pattern to soil Ca in the fertilized control relative to the other treatments (Table 5). This effect may be due to competition in the soil between Ca and Mg, which have similar exchange characteristics. The Ca was enriched 77 times in the applied biosolids relative to Mg, monopolized a greater number of the divalent cation exchange sites, allowing proportionately more Mg to leach or preferred Mg uptake of the small amount by plants compared to the fertilized control.

Levels of soil Mn, Fe, Al, and Cu all exhibited similar patterns over time (Table 5). In the fall of 1994, these metal levels typically showed little difference, but the 0:1 S:B treatment tended to be depressed compared to the others. In succeeding samplings, the biosolids treatments were enriched relative to the fertilized control. The delayed detection is likely due to the time necessary for the biosolids metals to convert from their very high pH stable forms, and to become acid-extractable in the soil. Soil Zn levels, while not significantly different in 1997, seemed to be higher in the fertilized control relative to the other treatments. This may be due a plant uptake effect, where the higher plant yields on biosolids treated plots depleted soil Zn, or more likely a result of the difference in soil pH. Soil B levels only differed in the fourth year of the experiment (Table 5). Boron levels in the 1:1 and 2:1 S:B treatments were higher than those of the fertilized control. It is unclear whether this difference is a residual effect of the biosolids and sawdust amendment as the material turned over, or was possibly a pH/solubility effect.

Soil P levels were initially nearly equal, but the biosolids amended treatments remained high while the fertilized control available-P levels decreased abruptly (Table 5) over time. Orthophosphate fertilizer was more soluble and hence quickly depleted from the control via plant uptake and soil sorption, while the

Table 5. Soil pH, and extractable nutrient and metals in November 1994, January 1996 and 1997.

Date	Treatment	Dilute Acid Extractable Elements in Soil (mg/kg)									
		K	Ca	Mg	Zn	Mn	Fe	Al	Cu	B	P
Nov-94	0:I S:B	65b*	4592a	118b	71a	13a	8.69a	98a	0.59a	0.48a	45a
	0.5:1 S:B	60b	4033a	125b	59a	21a	14.41a	178a	0.90a	0.44a	57a
	1:1 S:B	99a	4348a	124b	30a	20a	18.09a	189a	1.07a	0.48a	56a
	2:1 S:B	73b	4002a	126b	30a	24a	27.92a	237a	1.37a	0.42a	82a
	Fert. control	77ab	2076b	174a	72a	26a	24.96a	170a	0.92a	0.49a	49a
Jan-97	0:1 S:B	39a	2951a	101b	29a	33a	31.37a	268a	1.77a	0.45ab**	59a
	0.5:1 S:B	45a	2487b	110b	25a	39a	35.41a	261a	1.72a	0.45ab	56a
	1:1 S:B	53a	2843a	122b	19a	37a	30.05a	283a	1.38a	0.51a	59a
	2:1 S:B	48a	2688ab	117b	19a	39a	33.52a	264a	1.49a	0.50a	55a
	Fert. control	46a	1350c	192a	47a	22b	14.19b	119b	0.65b	0.40b	14b

*, ** Values followed by the same letter within a year are not significantly different at p = 0.05 and p = 0.10 level respectively

very large mass of P from the biosolids treatments was supplied from a mix of inorganic and organic forms, which provided higher and longer term supplies of extractable P.

Leachate Properties

The volume of leachate followed an expected seasonal cycle. There were no leachates collected during the summer until the late fall, essentially corresponding with the periods of greatest plant growth and transpiration. The leaching season typically lasted from October to the last collection in April. The 0:1 S:B treatment generated higher concentrations of NO_3-N than all other treatments during the first leaching season (1993/1994) (Table 6, Figure 1). These results, along with the relatively consistent pattern of NO_3-N levels decreasing with increased amounts of sawdust (Table 6), suggest that additions of C in the form of sawdust were effective in limiting NO_3-N leaching via microbial immobilization processes.

Nitrate-N levels averaged above the 10 mg/L EPA drinking water standard for much of the first winter in the 0:1 S:B and 0.5:1 S:B treatments and for 0:1 S:B on the first leaching event of the third year (Figure 1). The higher S:B treatments and control occasionally exceeded the 10 mg/L level, but time-averaged values were below this threshold. While there were occasional spikes of NO_3-N leaching, especially at the beginning of a leaching season (e.g. the third season) over time, all treatments approached zero NO_3-N leaching by the fourth season (Figure 1).

While the NO_3-N levels exceed the drinking water standard for some plots in all treatments including the fertilized control at some point during the experiment, there is likely not a major ground water contamination risk because of the further dilution that would have occurred between the near-surface lysimeters and the actual water table. Based upon the volume of leachate removed from each lysimeter and the concentration, nitrate-N can also be expressed on a mass basis (Table 6). These values closely follow the nitrate-N concentration values except during the first leaching season. During the first season, the volume of leachate from the 2:1 S:B treatments was much higher than the other treatments, actually causing it to have the highest nitrate leaching losses, 13.35 kg/ha/season NO_3-N (Table 6). The higher leachate volume from the 2:1 S:B during the first season was presumably due to the delayed vegetation establishment as seen in the May 1994 standing biomass (Table 2), leading to much lower transpiration losses. Enhanced infiltration due to the sawdust's effect on relative macroporosity may also have been a factor.

Table 6. Nitrate-N leached expressed on a concentration and mass basis for each treatment during each leaching season.

Treatment	Mean Nitrate-N (mg/L)	Nitrate-N leached (kg/ha/season)
	10/93 – 5/94	
0:1 S:B	21.4a*	9.27ab*
0.5:1 S:B	10.8b	6.60bc
1:1 S:B	5.1c	2.52cd
2:1 S:B	6.2c	13.35a
Fert. Control	7.4bc	1.61d
	9/94 – 5/95	
0:1 S:B	4.1a	3.19a
0.5:1 S:B	2.0a	2.07a
1:1 S:B	1.6a	0.92a
2:1 S:B	0.4a	0.31a
Fert. Control	0.4a	0.33a
	9/95 – 5/96	
0:1 S:B	6.7a	7.88a
0.5:1 S:B	4.0a	6.45a
1:1 S:B	3.4a	4.12a
2:1 S:B	3.2a	5.37a
Fert. Control	1.5a	2.54a
	9/96 – 5/97	
0:1 S:B	0.2a	0.10a
0.5:1 S:B	0.2a	0.04a
1:1 S:B	0.1a	0.01a
2:1 S:B	0.0a	0.01a
Fert. Control	0.1a	0.04a

* Values followed by the same letter within the same season and column are not significantly different at $p = 0.05$ level.

Conclusious

The plant yield of the 2:1 sawdust:biosolids treatment was lower than the fertilized control, while the 1:1. 0.5:1, and 0:1 treatments produced the same or more standing biomass than the fertilized control during the first winter and spring. Following the first growing season, the 0:1, 0.5:1 and 1:1 S:B treatments all produced plant yields greater than the 2:1 S:B and the fertilized control. While the biosolids treatments elevated extractable metal levels in the soil, they were not above acceptable ranges and did not suppress plant growth or pose bioaccumulation threats (Boswell, 1975). The biosolids amendments improved soil properties though enhanced organic matter levels and

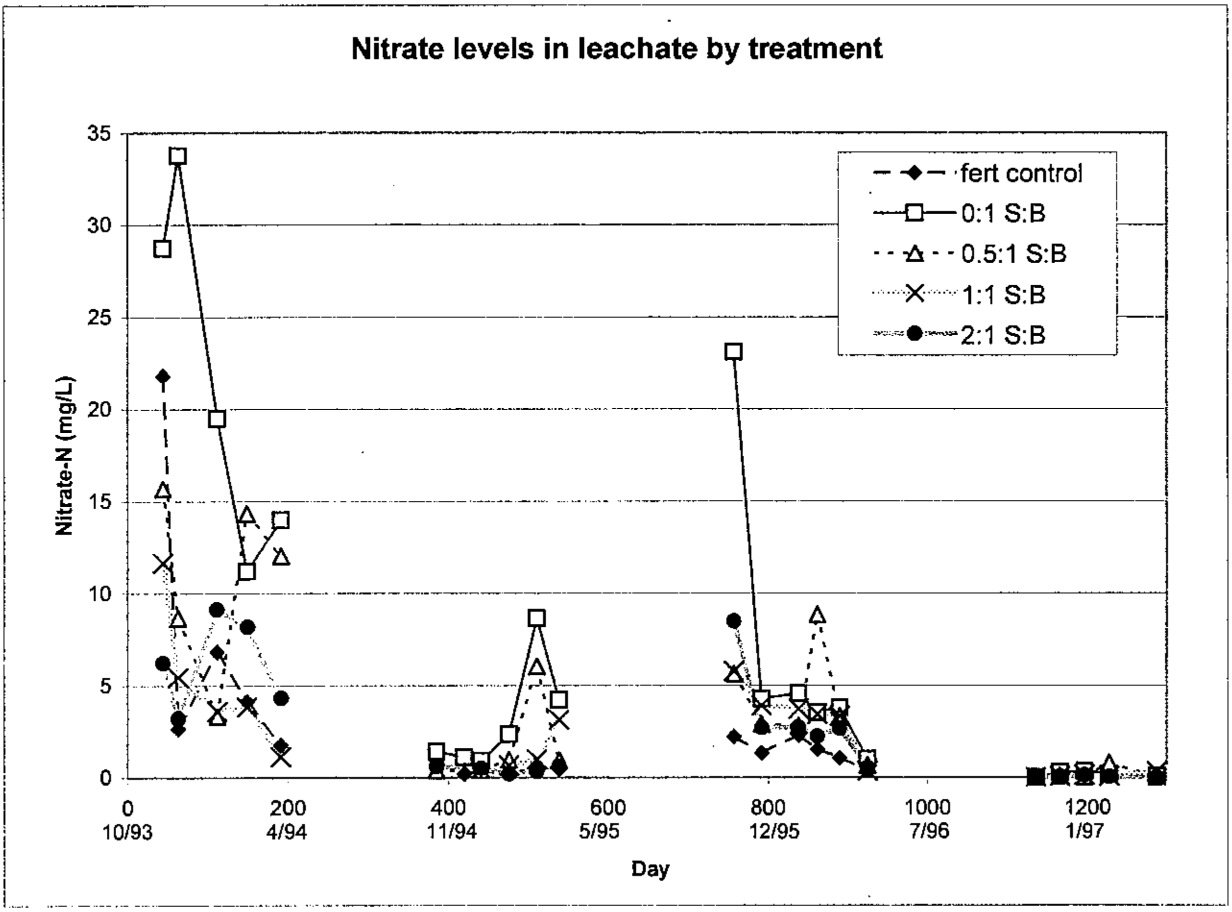

Figure 1. Nitrate-N (mg/l) in leachate for each treatment during the four years of the study.

associated physical effects by keeping P available throughout the experiment and by keeping the soil pH higher than the fertilized control.

A soil amendment of 90 Mg/ha of biosolids in a 0:1 S:B ratio produced significantly higher leachate NO_3-N content than the 1:1 and 2:1 ratios and the fertilized control during the first winter. During the first few months after the amendments were applied, NO_3-N levels remained high (over 10 mg/L) in all treatments. In the following months, the 1:1 S:B, 2:1 S:B, and control NO_3-N levels fell below 10 mg/L, while the 0.5:1 and 0:1 treatments remained elevated. Even though all treatment leachates were acidic, the treatments that contained sawdust buffered the pH at higher levels than the 0:1 and control treatments.

The 1:1 ratio of sawdust to biosolids was the best treatment evaluated here because it produced higher plant yields while simultaneously reducing NO_3-N leaching to acceptable levels by the end of the first winter, unlike the 0.5:1 or 0:1 treatments. While many of the effects of the soil amendments are short term, the increased P-availability and organic matter levels in the soil associated with biosolids treatments will lead to long term improvement of soil quality.

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