Research Article

Impact of Waste Materials and Organic Amendments on Soil Properties and Vegetative Performance

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Waste materials, and materials derived from wastes, possess many characteristics that can improve soil fertility and enhance crop performance. These materials can be particularly useful as amendments to severely degraded soils associated with mining activities. This study evaluated biosolids, composts, log yard wastes, and two organic soil treatments for improved soil fertility and vegetative performance using side-by-side comparisons. Each plot was seeded with a standardized seed mix and evaluated for a series of soil chemical and physical parameters, total vegetation response, species diversity, ecological plant response, and invasion indices. All treatments were successful at improving soil fertility and promoting a self-sustaining vegetative cover. The level of available nitrogen had a strong impact on vegetative coverage, species distribution, and extent of unseeded vegetation. For example, high nitrogen treatments promoted a grass-dominated (low forb) plant community with a low content of unseeded vegetation. In contrast, low nitrogen treatments promoted a more balanced plant community with a mixture of grass and forb species and greater susceptibility to unseeded vegetation establishment.

1. Introduction

The use of waste materials as soil amendments has received increased attention in recent years for agronomic applications as well as soil reclamation projects. Adding these materials to soils can be viewed as serving a dual purpose: (1) for disposal of solid waste from municipalities and agricultural operations and (2) as a means to improve chemical and physical soil properties which in turn promotes improved crop performance.

A variety of materials have been investigated for their suitability as soil amendments. For example, applications of composted municipal solid waste and composted crop residues were shown to increase soil fertility and improve structural stability in agricultural soils [1, 2]. Similarly, municipal biosolids have been used to improve soil chemical and physical properties in numerous studies [3–5]. Log yard fines (LYF) can increase water holding capacity and porosity [6] but have also been shown to reduce crop performance due to nitrogen immobilization [7]. For this reason, biosolids are often mixed with LYF and other wood byproducts as

a means to reduce C : N and maintain nitrogen availability [8, 9]. Others have utilized agricultural limestone or wood ash in biosolids mixtures to reduce metal bioavailability [3, 10].

The chemical properties of the waste material can also have significant impacts on crop performance. For example, a high nitrogen content favors fast-growing grass species which is often desirable for reclamation and revegetation projects [11]. However, the dominance of grasses can lead to competitive exclusion of forb species [12] and can initiate a strong decline in plant species richness [10, 13]. Additional soil factors including pH, electrical conductivity, water holding capacity, and available phosphorus have also been shown to impact plant community composition [14].

Several microbial processes including substrate-induced respiration, potential ammonium oxidation, nitrogen mineralization, and enzyme activity increased in response to compost application [15, 16]. Multiple studies using a variety of substrates found no negative impacts on microbial diversity [16–18]. The potential does exist for deleterious impacts of

organic waste additions, due primarily to the presence of heavy metals [19–21] and nutrient runoff [22, 23]. Many of these concerns are addressed by careful characterization of the waste material and through adjustment of the application rate [24, 25].

The above discussion indicates that a given waste material must be evaluated for both its beneficial components and negative impacts within the context of a specific land use and crop performance objective. Given the variety of waste material types available, it was desirable to conduct a side-by-side comparison in order to evaluate each material's impact on crop performance under the same environmental and soil conditions. Furthermore, although multiple investigations have documented the impact of organic amendments in agricultural systems, far fewer studies have investigated these impacts in soil-plant systems associated with mine site reclamation. In many cases, mine spoils represent a completely destroyed soil-plant ecosystem. Restoration of these sites provides a unique opportunity to study the development of newly placed soils and associated succession of plant communities as modified by organic amendments. In the current study, seven waste-based and organic soil amendments were evaluated for their impacts on soil fertility and crop performance. The "crop" in this case was a grass-forb seed mix being evaluated for revegetation of the severely degraded site. Specific research objectives were to document (1) changes in soil properties, (2) overall vegetation success, and (3) plant community diversity as a function of organic amendment.

2. Methods

2.1. Site Description. The Silver Dollar Mine site is located west of Osburn, Idaho, USA (47°30.22′N; 115°59.39′W). The site is dominated by a waste rock pile produced during mine development and sorted from the ore during the mining process. The experimental plots were situated on a steep north-facing slope (1 : 2 slope, H : V) at an elevation of about 760 m. Average total monthly precipitation ranged from 3.8 cm in July to 11.4 cm in November, with a total annual precipitation of 96 cm. Average monthly temperatures were 0.5/−6°C (max/min) in January and 25.8/8.4°C in August.

2.2. Site Preparation/Plot Installation. The site was regraded using a Cat D5 Dozer, and nine plots (6 m × 30.5 m) were installed with a berm (1 m × 0.6 m) separating each plot. The western- and eastern-most plots were reserved for controls; the remaining plots were assigned on a random basis. Amendment types, application rates, and application methods were specified by the collaborators participating in the study (Table 1). Project collaborators included the local wastewater treatment facility (biosolids + woodash), a local lumber mill (log yard fines (LYF) + urea fertilizer), and two commercial composts (biosolids- and wood products-based). In addition, two commercial organic amendments were investigated. Kiwi Power is designed to reestablish mycorrhizal fungi, soil bacteria, and other beneficial soil organisms necessary to restore severely degraded soils. Biosol

Table 1: Amendment type, application rates, and application methods.

Amendment type	Rate and application method
Control (topsoil)	30 m³ topsoil (surface applied, not incorporated, amendment depth approx. 15 cm)
Biosolids + woodash	20 m³ class B biosolids mixed with wood ash (0.75 : 1) (surface applied, not incorporated, amendment depth approx. 10 cm)
Log yard fines (LYF) + urea fertilizer	37 m³ log yard fines (<3/4″) mixed with urea fertilizer (10% v/v) (surface applied, not incorporated, amendment depth approx. 15 cm)
Kiwi Power	Fertile Fibers Plus, Kiwi Power, Strong Hold + Tacker and Atlas Soil Lock (materials were mixed and surface applied by hydroseeder)
Biosolids-based compost	15 m³ of compost (surface applied, not incorporated, amendment depth approx. 10 cm)
Wood products-based compost	15 m³ of compost (surface applied, not incorporated, amendment depth approx. 10 cm)
Biosol	38 kg Biosol Mix (7-2-3) plus 2.3 kg Wood Fiber Mulch (materials were mixed and surface applied by hydroseeder)
Log yard waste (LYW)	15 m³ of log yard waste (surface applied, not incorporated, amendment depth approx. 10 cm)
Control (fertilizer)	23 kg of fertilizer (16-16-16) plus tackifier (materials were mixed and surface applied by hydroseeder)

is an organic fertilizer material designed to increase microbial biomass and build humus. Installation of the plots began September 25, 2002 and concluded October 23, 2002. Each plot was seeded, either by hand or by hydroseeding, using a standardized seed mix (Table 2). No additional work, modification, or maintenance was conducted on the plots for the remainder of the five-year study with one exception—the LYF + urea plot was reseeded in August 2003. This was necessary due to a complete failure of seed germination in year 1.

2.3. Soil and Vegetation Assessment. The plots were inspected on a monthly basis during each field season beginning in April 2003 and concluding in August 2007. Quantitative determination of revegetation success was conducted each July using Bureau of Land Management standard methods [26]. Percent coverage was measured using a cover-point optical projection scope. One hundred points were recorded at 1 m intervals along a randomly located transect within each plot. Each point identified an individual plant, rock, bare soil, or litter.

Duplicate soil samples were collected from the control plots following regrading but prior to addition of plot

TABLE 2: Composition and application rates of standardized seed mix.

Common name	Species/variety	Amount/acre	Pct by wt.	Min. pct.
Slender wheatgrass	*Elymus trachycaulus* ssp. *Trachycaulus* var. Revenue	6.4 kg	22.3	21.9
Idaho fescue	*Festuca idahoensis* var. Joseph	3.9 kg	13.4	13.2
Sheep fescue	*Festuca ovina* var. Covar	3.2 kg	11.1	10.9
Mountain brome	*Bromus marginatus* var. Bromar	3.5 kg	12.2	12.0
Meadow brome	*Bromus biebersteinii* var. Paddock	3.9 kg	13.4	13.2
White yarrow	*Achillea millefolium*	0.34 kg	1.1	1.1
Blue flax	*Linum lewisii* var. Appar	1.9 kg	6.7	6.6
Rocky Mountain penstemon	*Penstemon strictus*	0.68 kg	2.2	2.2
White dutch clover	*Trifolium repens* L.	0.23 kg	0.8	0.8
Canada bluegrass	*Poa compressa*	0.34 kg	1.1	1.1
Big bluegrass	*Poa ampla* var. Sherman	0.68 kg	2.3	2.3
Canby bluegrass	*Poa canbyi* var. Canbar	0.68 kg	2.2	2.2
Cicer milkvetch	*Astragalus cicer*	3.2 kg.	11.1	10.9
Fireweed	*Epilobium angustifolia*	0.28 kg	0.1	0.1
Weed seed	—	—	—	0.5 (Max)
Inert and other crop	—	—	—	1.5 (Max)

amendments; these results are reported as the control (unamended) in the following figures and tables. Soil profile characteristics were evaluated in the field at the end of year 5. During years 1, 3, and 5, a composite (3x) soil sample was collected from the 0–10 cm depth of each plot. Soil fertility parameters (ammonium-N, nitrate-N, available P and K, pH, and EC) and physical properties (percent sand, silt, clay, coarse fragments, and textural class) were determined using standard methods [27]. Available N was calculated as the sum of ammonium- and nitrate-N. Organic matter content was determined by colorimetry [28]. Total recoverable metals were determined using EPA Method 3050B/6010 [29]. All laboratory work was conducted at the University of Idaho Analytical Sciences Laboratory. Standard quality assurance/quality control protocols were followed for all analytical work [30].

2.4. Data Analysis. Diversity-related indices, namely Shannon-Wineer index (H′) and evenness (E), were calculated by year for each treatment. The invasion index (I) was also calculated for each treatment where I is the number of introduced species/total number of species. Diversity indices and plant cover data were subjected to analysis of variance using the generalized linear model [31]. Single degree of freedom contrasts were used to compare mean responses. A 95% significance level ($P < 0.05$) was used for all statistical comparisons.

3. Results and Discussion

3.1. Soil and Amendment Properties. Following site preparation but prior to amendment application, the surface soil material was a mixture of waste rock and fine material. The unamended control (Table 3) exhibited properties endemic to the Silver Dollar site, namely an alkaline (pH 8.3) sandy loam with 58% coarse fragments. The electrical conductivity (EC) of the unamended control was 0.35 dS/m and heavy

metal concentrations (As, Ba, Cd, Cr, Pb) were below hazard limits for regulated metals [32]. This is not surprising since milling and smelting activities took place off-site. The macronutrient content of the unamended control was quite low with available N and P concentrations of 1.5 ug/g and 1.0 ug/g, respectively (Figure 1). Organic matter content was also low at 0.9% and available K was moderate at 79 ug/g. Thus, the chemical and physical data indicate that low soil fertility was the primary factor limiting sustainable plant growth in the unamended soil. A secondary issue was the low water holding capacity.

Each treatment decreased soil pH relative to the unamended control (Table 3). The pH of the amended plots ranged from 6.3 to 7.8 with the biosolid + woodash and control (fertilizer) treatments exhibiting the highest pH. Overall, the pH remained relatively consistent among the amended plots throughout the five-year study period (data not shown). The highest EC values were observed in the biosolids + woodash and LYF + urea treatments (Table 3). Although these higher EC values are near critical values for agronomic crops (2–4 dS/m), none of the vegetation exhibited symptoms of a salinity problem.

During the first year (2003), the organic matter content varied from ~1% in the controls and liquid-based amendments (Kiwi Power and Biosol) to 15–34% in the solid-based amendments (biosolid, composts, LYF, and LYW) (Figure 1(a)). The organic matter content in several of the treatments (biosolids, LYF + urea, and biosolids-compost) increased between 2003 and 2005 (Figure 1(a)). Each of these treatments exhibited substantial vegetative growth resulting in high crop residues and organic carbon recycling. Each treatment associated with the high organic matter amendment (biosolid, composts, LYF, and LYW) exhibited a marked decrease in organic matter between 2005 and 2007.

Each treatment increased the available P and K content with the extent of increase being strongly dependent on

Table 3: Metal content, electrical conductivity (EC), particle size distribution, and soil texture for unamended and treated plots.

|	As (ug/g)	Ba (ug/g)	Cd (ug/g)	Co (ug/g)	Cr (ug/g)	Cu (ug/g)	Fe (ug/g)	Mn (ug/g)	Mo (ug/g)	Ni (ug/g)	Pb (ug/g)	Zn (ug/g)	pH	EC dS/m	Sand %	Clay %	Silt %	>2mm %	Texture
Unamended control	59	220	0.08	15	13	81	20000	1400	<3.8	16	100	170	8.3	0.35	66	16	18	58	Sandy loam
Control (topsoil)	16	240	<0.75	13	54	25	27000	830	<3.8	32	19	91	6.3	0.24	46.4	9.6	44.0	59	loam
Biosolids + woodash	34	850	2.8	11	58	130	16000	2200	<3.8	45	34	470	7.5	3.8	72.4	7.6	20.0	35	Sandy loam
LYF + urea	12	310	<0.75	11	71	33	22000	930	<3.8	43	22	110	7.2	3.4	52.4	7.6	40.0	38	Sandy loam
Kiwi Power	46	230	<0.75	18	35	140	29000	2400	4.6	32	26	74	7.8	0.78	70.4	11.6	18.0	57	Sandy loam
Biosolids compost	22	260	0.75	13	63	110	22000	1400	4.6	41	37	190	7.4	1.3	56.4	7.6	36.0	34	Sandy loam
Wood compost	33	400	<0.75	8.8	74	130	17000	1500	<3.8	41	29	110	6.5	0.31	66.4	9.6	24.0	51	Sandy loam
Biosol	47	480	<0.75	12	66	96	23000	2000	<3.8	39	80	150	7.8	1.6	60.4	15.6	24.0	57	Sandy loam
LYW	23	240	<0.75	7.3	62	35	16000	1100	<3.8	36	16	78	6.8	0.54	64.4	9.6	26.0	33	Sandy loam
Control (fertilizer)	62	350	3.7	11	46	86	22000	1300	<3.8	31	99	920	7.8	0.80	66.4	13.6	20.0	68	Sandy loam

(a)

(b)

(c)

(d)
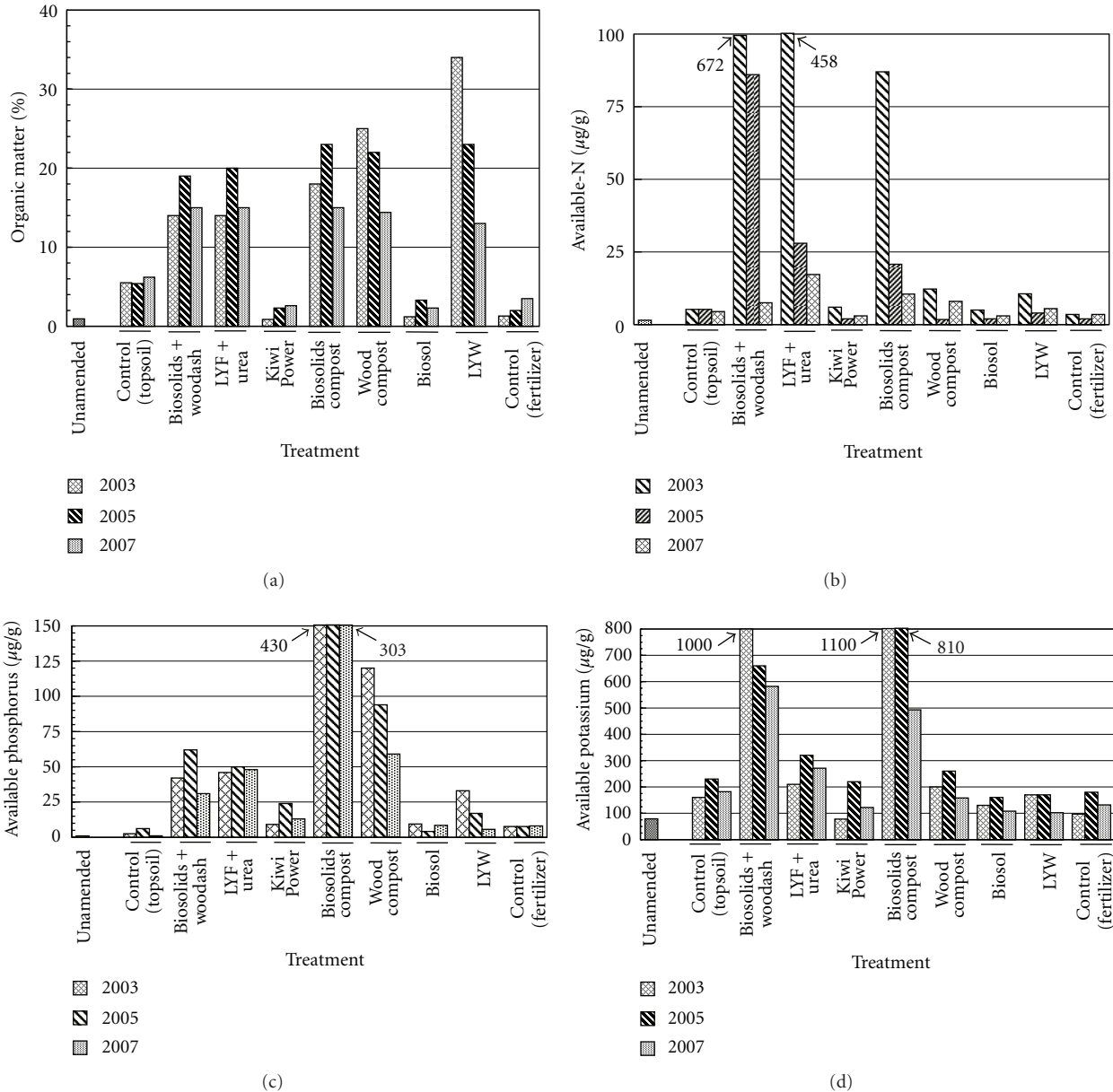
FIGURE 1: Trends in (a) organic matter content, (b) available N, (c) available phosphorus, and (d) available potassium in the unamended and treated plots for years 2003, 2005, and 2007.

the nature of the amendment (Figures 1(c) and 1(d)). Available P values ranged from <2 to >600 ug/g while available K ranged from 80 to 1000 ug/g. To put these numbers into perspective, available P and K levels in excess of 8 and 100 ug/g, respectively, are considered sufficient for nonirrigated legume-grass pastures in northern Idaho [33].

Available N also varied significantly among the treatments, ranging from ~5 ug/g in the Kiwi Power and Biosol to >450 ug/g in the biosolids and LYF + urea treatments (Figure 1(b)). Each treatment with high available N (biosolid, biosolid-compost, and LYF + urea) exhibited a substantial decrease between 2003 and 2005, and again between 2005 and 2007. Potential fates of available

N include leaching, plant uptake, and volatilization. A significant fraction of available N was lost via surface runoff as previously described by McGeehan [34] and this was most significant in the biosolids + woodash, LYF + urea, and biosolids-compost treatments. The high available N associated with these plots also supported very heavy vegetative growth, primarily of perennial grasses which exhibit high uptake rates and N sequestration [35, 36]. However, given the magnitude of declines observed, it is likely that ammonia volatilization played the most significant role in decreased available N. Large and rapid loss of N is commonly observed in surface-applied biosolids with volatilization rates exceeding 50% of total N [37–39].

This mechanism was further enhanced by the high pH levels.

3.2. Profile Properties. The addition of the various amendments had differing impacts on the soil profile of each plot. It should be noted that a true pedogenic soil profile takes hundreds to thousands of years to form. Thus, it is somewhat of a stretch to describe the profile of each plot using standard soils terminology. Nonetheless, the amendments did alter the surface properties of each plot in ways that will have lasting impacts on the sustainability of the plant cover. For example, the addition of roughly 20 m^3 of biosolids, compost, or log yard waste resulted in an overburden depth of 10–15 cm. This overburden tended to be dark in color with a very friable (easily crumbled) texture. Such characteristics are associated with highly productive and fertile topsoil and, hence, these plots supported very good plant growth resulting in the presence of profuse fine roots in the overburden. Since the organic materials were surface applied but not incorporated, there was an abrupt boundary between the overburden and underlying waste rock with very few roots penetrating this boundary. This abrupt boundary remained very distinct throughout the study. Also, the physical condition of the overburden improved over the course of the 5-year study. For example, the biosolids were very sticky and tended to smear during application. However, as this material dried and weathered for several years, the result was a very light material with physical properties that are ideal for plant growth. Likewise, the log yard waste and composts underwent both physical and biological weathering, resulting in a very friable material with excellent tilth and other desirable physical properties.

In contrast, the Kiwi Power, Biosol, and Fertilizer Control did not receive large quantities of organic amendments. Consequently, these plots exhibited a thin organic surface layer developed from decaying plant debris. Despite the lack of a thick, organic overburden, these plots still supported good plant growth as evidenced by the moderate root presence. It is likely that these plots will continue to build organic matter content over time and slowly improve soil physical properties.

3.3. Vegetation Assessment

3.3.1. Plant Cover. Each treatment was successful in promoting a self-sustaining plant cover during 2003 and maintaining plant growth throughout the five-year study (Figure 2). During the first year, the extent of coverage varied considerably, ranging from 19% to 77% in the LYW and biosolid-compost treatments, respectively. The wood-compost treatment exhibited low coverage in year 1, most likely as a result of a high C : N. Plant coverage increased in all treatments between years 1 and 2. These changes were associated with increased growth of grass species in the biosolids + woodash, biosolids compost, and Biosol plots and increased forb growth in the Kiwi Power, wood compost, and LYW plots. Slender wheatgrass and brome species were the most extensive grasses observed during years

1 and 2 while yarrow and white dutch clover were the most frequently observed forbs. The majority of plots maintained plant coverage in the 75–90% range from year 3 to year 5 (Figure 2).

3.3.2. Unseeded Vegetation. Unseeded vegetation accounted for a significant portion of coverage in several treatments during the study period (Figure 2). For example, the topsoil-control exhibited a high incidence of weeds beginning in year 1 with >50% of the plant cover due to the establishment and growth of hare's foot clover. In contrast, the Kiwi Power, wood compost, and LYW plots did not exhibit substantial increases in weeds until years 3 and 4 (Figure 2). These large increases were primarily the result of black medic and sweet clover. It should be noted that several plots (i.e., biosolids + woodash, LYF + urea, biosolids compost, and Biosol) exhibited very little weed invasion. The majority of the unseeded species can be classified as common weeds of the Northwestern US [40] that are easily disseminated by wind, animals, and other vectors. However, given the disproportionately high percentage of unseeded vegetation present in the topsoil-control in year 1, it is likely that many weed seeds were transported to the site in the topsoil amendment. The role of topsoil as a seed bank is well established, and imported soil has been reported to introduce both desirable and undesirable invasive species [41, 42].

3.3.3. Species Distribution and Diversity. Grass species dominated the plant communities in the high N treatments. As an example, the species composition by year for the biosolids + woodash treatment is plotted in Figure 3(a). Similar results were obtained for the LYF + urea and biosolid-compost treatment. Although wheatgrass was the dominant grass in year 1, the 2004–2007 data (years 2–5) show a trend of declining wheatgrass with concurrent increases in bromes and fescues in of the grass-dominated plots. It is unclear whether the gradual decline in wheatgrass is a natural successional characteristic or a response of this species to a decrease in available N. The lower N treatments exhibited a more even distribution between grass and forb species throughout the study period. As an example, species composition for the wood-compost is plotted in Figure 3(b). Similar results were obtained for the Kiwi Power and LYW treatments. Yarrow, fescue, and bromes tended to increase steadily in years 1, 2, and 3. White clover was common on several of the lower N treatments in year 1 but was rarely encountered during years 2–5. In contrast, cicer milkvetch was not observed during years 1 and 2 but increased significantly during the final three years of the study.

The relationship between vegetation and N availability was further evaluated by pooling the plant response data into high versus low treatments for statistical analysis. As shown in Figure 4(a), significantly higher Shannon diversity indices (H′) were obtained for the high N treatments in three out of the five study years. This reflects the greater number of grass species associated with these treatments, particularly in the final two years. Species evenness (E) was very similar between the high and low N treatments (Figure 4(b))
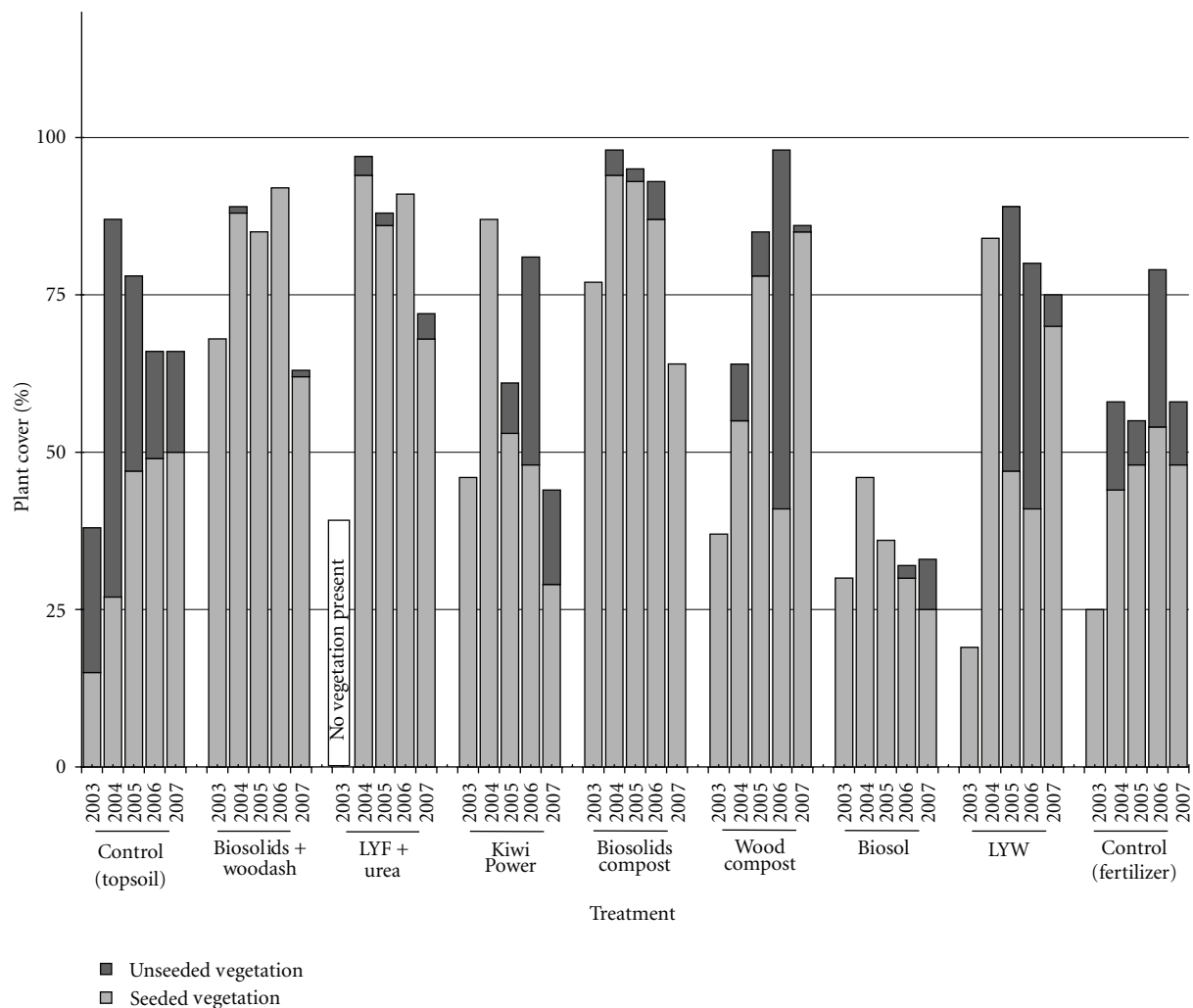
FIGURE 2: Comparison of total plant cover across all treatments for years 2003, 2004, 2005, 2006, and 2007.
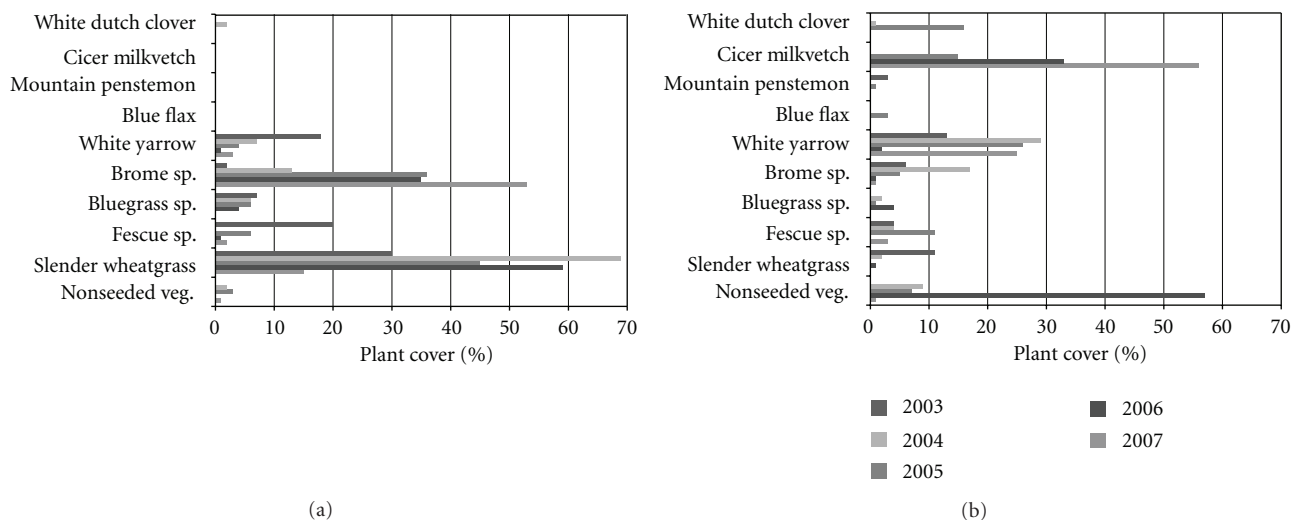

FIGURE 3: Species composition on (a) high nitrogen treatment (biosolids + woodash) and (b) low nitrogen treatment (wood compost) for years 2003, 2004, 2005, 2006, and 2007.
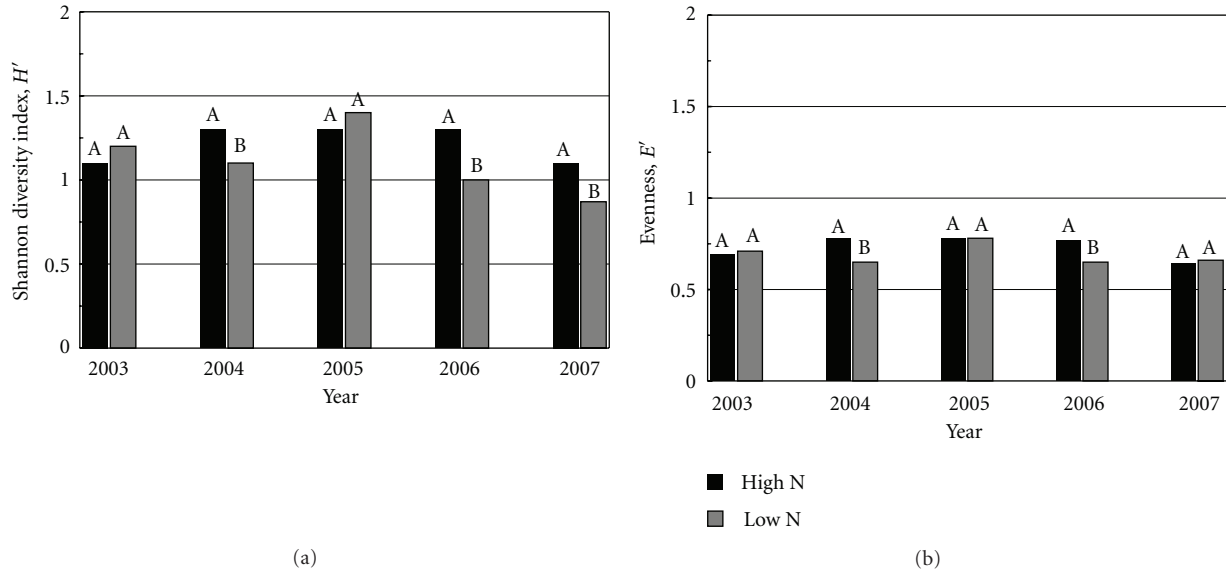
(a)

High N

Low N

(b)

FIGURE 4: Mean responses for (a) Shannon diversity index and (b) species evenness in pooled high versus low nitrogen treatments by year. Responses associated with different letters are significantly different ($P < 0.05$).

(a)

Grass

Forb

(b)
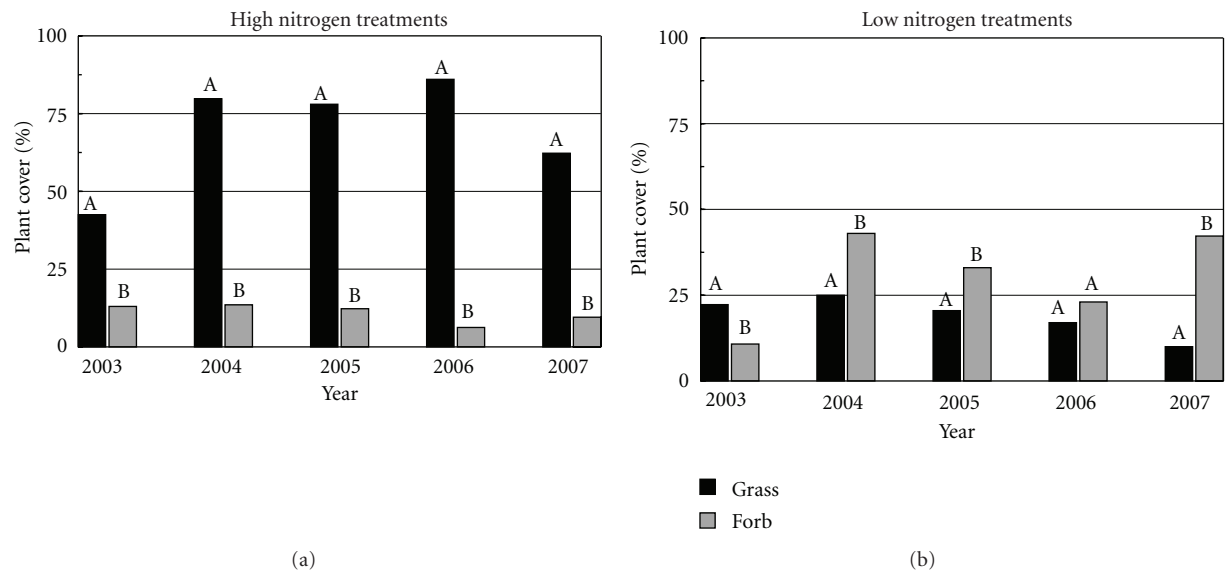
FIGURE 5: Mean vegetation response in (a) pooled high nitrogen treatments and (b) pooled low nitrogen treatments by year. Responses associated with different letters are significantly different ($P < 0.05$).

indicating no significant differences in the relative abundance of species between these groups, with the exception of 2006.

A comparison of vegetative response based on ecological vegetative groupings (grass versus forb) is shown in Figure 5. In each of the five years, the percent cover due to grasses was significantly higher than forb cover in the pooled high N treatments (Figure 5(a)). In contrast, forbs were significantly higher in 3 of 5 years in the low N treatments. Furthermore, the invasion index (I) was markedly impacted by N treatment. Counts of weed species were very low in the first two years of the study but increased substantially in the low N treatments in Years 3, 4, and 5 (Figure 6).

Several studies report increased weed growth in high nitrogen environments [43, 44]. The opposite trend was observed in our study where, as Figure 6 clearly shows, an inverse relationship exists between available nitrogen and the invasion index. That is, a low invasion index is associated with the high N treatments and vice versa. A likely mechanism explaining this result is a competition for
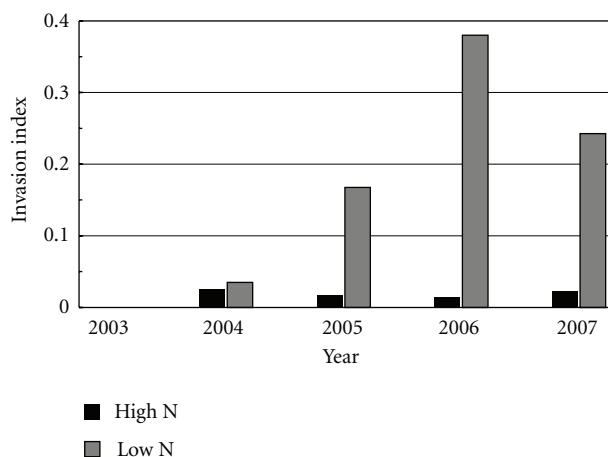
FIGURE 6: Mean invasion indices in pooled high- versus low-pooled nitrogen treatments by year. Note: the number of zero values precluded statistical analysis.

nutrients and light which can favor rapidly growing grasses [45, 46]. The growth habit of the weed species may be an additional factor with low, radially spreading species being less able to compete for light and, hence, be favored by the more open cover of the low nitrogen treatments [47].

4. Conclusions

The overall goal of this study was to evaluate waste-based and organic amendments for their ability to improve soil fertility and crop performance. Each amendment resulted in significant improvements in soil fertility parameters and all were successful in establishing plant cover during the first growing season and sustaining this cover throughout the five-year study.

Organic matter content and available N, P, and K were significantly increased by the various amendments although the extent of increase was determined by the composition of the amendment. All solid amendment types (composts, biosolids, and LYF/LYW) greatly increased the organic matter content. However, only the biosolids, biosolid-based compost, and LYF mixed with urea fertilizer contributed large amounts of available N. The wood products-based compost and LYF contributed lower amounts of available N. Each treatment associated with high inputs of organic matter and available N exhibited significant declines in these properties over the course of the study.

The fertility status of each amendment had a strong impact on crop performance. More specifically, available nitrogen was a critical factor in determining total plant cover, species distribution, and the incidence of unseeded vegetation. For example, high nitrogen amendments promoted a grass-dominated cover with low numbers of forbs. Wheatgrass was the dominant species in these plots during years 1 and 2 but a more equal distribution of wheatgrass, bromes, fescues, and bluegrass was observed in years 3–5. Throughout the study, these plots had the highest plant coverage and maintained very robust and thick grass growth.

These characteristics were successful in preventing the establishment and spread of invasive weed species. In contrast, amendments with lower available nitrogen promoted a more diverse grass-forb mixture. No single grass species was dominant; instead a variety of grasses were intermixed with white yarrow, white clover, and cicer milkvetch. These plots had lower plant coverage and more patchy plant growth. Consequently, a higher incidence of invasive weed species was observed.

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