Long-Term Effects of Biosolids on Revegetation of Disturbed Sagebrush Steppe in Northwestern Colorado

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Abstract

A study was conducted to evaluate the long-term effects of biosolids amendment on restoration of disturbed sagebrush steppe habitat in northwestern Colorado. Twenty-four years after biosolids amendment, soil fertility and plant community development were studied in replicated plots receiving various biosolids amendments on two different substrates. The two substrates used were a subsoil, determined to have low initial fertility, and a topsoil over retorted shale substrate, determined to have relatively high initial fertility. Results suggest that biosolids amendments have long-lasting effects on soil fertility and plant community composition, but these effects vary between the two substrates that were utilized. Within the plots established on subsoil, the long-term effect of biosolids was a reduction in plant species diversity and dominance by perennial grasses. On the topsoil substrate, there was a decrease in perennial grasses and an increase in shrub dominance with increasing biosolids. Results demonstrate the importance of considering initial soil conditions, seed mixture, and biosolids application rate when using biosolids for restoration of disturbed sagebrush steppe habitat. The long-term effects of the biosolids treatments at this site demonstrate the need to consider restoration treatment effects over longer and more ecologically meaningful time frames.

Key words: ***Artemisia tridentata*, oil shale reclamation, shrubland, soil amendment.**

Introduction

Biosolids from municipal wastewater treatment facilities contain nutrients that can be used for plant growth and can thus be used as an amendment in the restoration of disturbed lands. The use of biosolids amendments in restoration can help meet restoration goals while at the same time reducing other undesirable biosolids disposal scenarios such as landfilling, ocean dumping, or incineration.

Biosolids are a good source of slowly released N for plants (Zebarth et al. 2000). Increased N fertility resulting from modest biosolids applications (25 Mg/ha) has been shown to increase perennial grass production by 300% in a Colorado sagebrush steppe community (Pierce et al. 1998). The improved grass production noted by Pierce and coworkers (1998) was coupled with improved forage quality in biosolids-amended plots. The use of other organic waste materials such as milk sewage has been shown to have similar beneficial effects on pasture production and tree growth in European agroforestry systems (Rigueiro-Rodriguez et al. 2000). Municipal biosolids have also been used to hasten revegetation following severe wildfires in the Rocky Mountains of Colorado (Meyer et al. 2001, 2004). On severely disturbed sites, biosolids amendments can significantly reduce soil erosion (Sort & Alcaniz 1996; Meyer et al. 2004) and improve water quality (Meyer et al. 2001) by promoting rapid establishment of plant cover.

When using biosolids amendments, it is important to carefully consider site and biosolids characteristics and application rates in order to avoid the negative effects of soil enrichment (Navas et al. 1999) such as salinity, metal toxicity, and the promotion of weedy and undesirable plant species. The coapplication of water treatment residuals with biosolids has been proposed as a way to adsorb excess phosphorus in some biosolids (Ippolito et al. 1999, 2002).

There have been relatively few long-term studies that have evaluated the use of biosolids as a revegetation or rangeland enhancement amendment within semiarid environments. Most biosolids studies have evaluated responses for only a few years so they do not reveal the effectiveness of soil amendments over longer, more ecologically meaningful, periods. Evaluation over longer time periods is essential to understand the ecological effects of using biosolids as a sustainable soil amendment and to understand the economic viability of such efforts.

The objectives of this study were to evaluate the long-term effects of biosolids application on plant community development and soil fertility 24 years after initial application. This study was conducted in plots established in 1977 as part of a larger study (Sabey et al. 1981) conducted in the Piceance Basin of northwestern Colorado. This study was established to investigate the long-term fertility

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requirements of nitrogen- and phosphorus-deficient soil materials disturbed by oil shale development. Replicated plots were initially treated with inorganic N and P fertilizer and biosolids mixed with wood waste. The study was monitored for several years after it was established. However, the long-term effects of these treatments have not been followed. In the present study we revisited the 1977 study plots to examine plant community and soil parameters. We hypothesized that the biosolids applications would have long-term influences on plant community development as evidenced by biomass and species diversity, and that the initial application of biosolids would result in enhanced long-term soil fertility.

Materials and Methods

The Piceance Basin study site is located 65 km northwest of Rifle, Colorado (UTM 12 S 722198 4420302) at an elevation of 2,030 m. The climate is semiarid with mean annual precipitation of 280 mm with about half of this as snowfall. Soil at the site is classified as Yamac loam (fine-loamy mixed, Borollic Camborthid) (USDA 1982), which supports a Big sagebrush (*Artemisia tridentata* Nutt.) steppe community.

Two sets of study plots were established in 1977 (Fig. 1). One set was established on disturbed topsoil (high-fertility plots) and the other on disturbed subsoil (low-fertility plots) because these substrates were the common growth media available following oil shale extraction. The topsoil plots were constructed with 61 cm of topsoil material that was mixed thoroughly and placed over retorted oil shale (produced by the Paraho method). The effects of this oil shale on vegetation have been examined for this site by Sydnor and Redente (2000). The subsoil plots were constructed with 122 cm of mixed subsoil material placed over a preexisting soil substrate. These two sets of plots are separated by approximately 15 m. In each set of plots, three replicates of each of 19 treatments plus one control were established. The treatments included various levels of inorganic N fertilizer applied annually or once, wood waste with N fertilizer, biosolids from a wastewater treatment lagoon in Hayden, Colorado, and inorganic N plus P fertilizer. The treatments we examined here are depicted in Figure 1 and include only biosolids and biosolids plus wood waste amendments. Amendments were surface applied and then worked into the substrate by rototilling.

Biosolids vary in the readily available forms of N depending on the C-to-N ratio and on the wastewater and biosolids treatment process used. Typically, with short-duration wastewater treatment, biosolids that are anaerobically digested can yield NH_4 concentrations of 3–6% (dry weight) and total N of 4–8% (dry weight). On the other hand, aerobically digested biosolids with the same wastewater treatment may yield a similar amount of total N, but very little NH_4. Wastewater lagoons, including the aerated lagoon at Hayden, Colorado, have extended treatment times, and the biosolids are in the treatment system for 10 or more years before removal from the lagoon. Biosolids produced from such lagoons contain more stable nutrients and have near equilibrium between carbon and nitrogen. Therefore, there is no great release of nitrogen per unit volume of biosolids applied. This may explain the necessity for the higher than typical biosolids land reclamation rates that were used when this project was initiated.

Following amendment applications, the plots were drill seeded with a mixture of grass, forb, and shrub species (Table 1) in November 1977. Rodent and lagomorph damage was extensive in the topsoil plots during the winter of 1978–1979, so the topsoil plots were reseeded in May 1979. During the spring and summer of 1979 approximately 15 cm of water was applied to the topsoil study plots over 6 weeks in order to facilitate establishment of the reseeded species.

Plant community and soil attributes were monitored in each plot during the first few years of the study.[1] Plots receiving biosolids amendments and control plots were revisited during 2001 to assess long-term responses to these treatments.

Soil samples were collected in July 2001 from each study plot. Seven randomly located soil cores were collected from a depth of 0–2.5 cm, and an additional set of seven cores was collected from 0–15 cm. The seven cores from each plot and depth were composited to yield two soil samples per plot. Samples were immediately cooled to 5°C and transported to the Soil Water and Plant Testing Laboratory at Colorado State University where they were analyzed for total nitrogen (LECO CHN-1000 analyzer, LECO Corporation, St. Joseph, MI, U.S.A.), plant-available nitrogen (KCl extract), organic matter (modified Walkley-Black), pH (saturated paste), electrical conductivity, extractable phosphorus (Bray), and other nutrients (AB-DTPA extract).

Aboveground plant biomass by species was collected in each plot from five randomly located 0.5-m^2 quadrats during early June and again in late July of 2001. Biomass was clipped to ground level, dried to constant mass, and weighed. The highest biomass for each species between the two sampling dates was used as the value for annual production for that species within each plot. In addition to the study plots, a reference area composed of an undisturbed sagebrush community located adjacent to the study plots was sampled in the same manner as the test plots in order to characterize the native late-seral vegetation. Soil samples were not collected in this reference area. Plants were grouped by life-history attributes into categories prior to analysis (Table 2).

Standard univariate statistical techniques were used to evaluate treatment differences. Means were compared using a Fisher's least significant difference (LSD) test on

[1] Results from this initial period were reported by Sabey et al. (1981). Readers who are interested in the initial findings from this study can find this report at the U.S. EPA Region 8 Biosolids Program Web site (http://www.epa.gov/region08/water/wastewater/biohome/biohome.html).

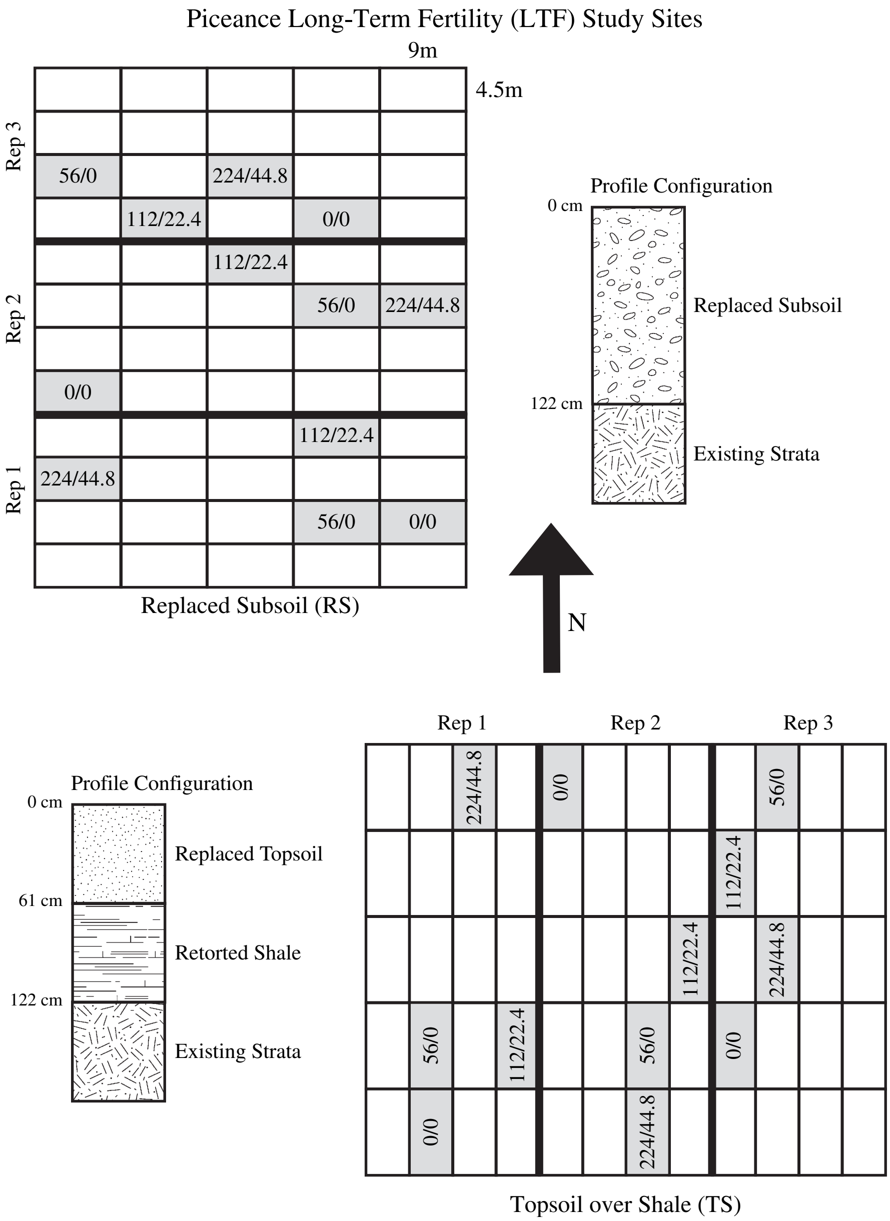

Figure 1. Study site map and profile configuration of the long-term fertility study plots at the Piceance Basin in northwestern Colorado, U.S.A. Plots used in this study are those with shading. Individual plots are 4.5 × 9 m. The distance between the two study panels is approximately 15 m. The two study panels differ in their substrate configuration. The replace subsoil (initial low fertility) plots were constructed in 1977 by placing 122 cm of mixed subsoil material over a preexisting soil substrate. The topsoil over shale (initial high fertility) plots were constructed in 1977 with 61 cm of topsoil material that was mixed thoroughly and placed over 61 cm of retorted oil shale (produced by the Paraho method). The numbers in the plots are rates of biosolids and wood waste in Mg/ha that were applied in 1977. Treatments were replicated three times on each substrate and were 56 Mg/ha of biosolids (56/0), 112 Mg/ha of biosolids plus 22.4 Mg/ha of wood waste (112/22.4), 224 Mg/ha of biosolids plus 44.8 Mg/ha of wood waste (224/44.8), and control with no amendments (0/0). All plots were drill seeded in November 1977 with the same seed mixture of grass, forb, and shrub species.

SAS version 8.01 PROC GLM (SAS Institute, Inc., Cary, NC, U.S.A.).

Results

Twenty-four years after treatment application we found significant differences between soil parameters in biosolids versus control plots (Table 3). Differences in soil parameters between amended and unamended plots were more pronounced on plots with subsoil as a growth medium.

Soil pH was lower on plots receiving biosolids or biosolids plus wood waste compared to control plots (Table 3). Soil organic matter continued to be higher on plots

Table 1. Species mixture and seeding rates used on the study plots in 1977 and 1979.

*Scientific Name**	*Common Name*	*Seeding Rate PLS (kg/ha)*
Pascopyrum smithii	Western wheatgrass	1.12
Elymus lanceolatus	Streambank wheatgrass	1.12
Pseudoroegneria spicata	Bluebunch wheatgrass	1.12
Achnatherum hymenoides	Indian ricegrass	1.12
Nassella viridula	Green needlegrass	1.12
Festuca trachyphylla	Hard fescue	0.56
Poa secunda	Sandberg bluegrass	1.12
Sporobolus airoides	Alkali sacaton	0.56
Sphaeralcea munroana	Munro globemallow	0.56
Hedysarum boreale	Northern sweetvetch	1.12
Penstemon palmeri	Palmer penstemon	0.56
Purshia stansburiana	Stansbury cliffrose	2.24
Ephedra viridis	Mormon tea	1.12
Atriplex canescens	Fourwing saltbush	1.12
Krascheninnikovia lanata	Winterfat	1.12
Purshia tridentate	Antelope bitterbrush	1.12

*Nomenclature follows USDA Plants Database (USDA & NRCS 2004).
PLS = pure live seed.

amended with biosolids or biosolids plus wood waste. However, the C-to-N ratio of the soils was generally lower on amended versus unamended plots, and greater amounts of nitrate were found in amended plots versus unamended plots. Levels of the other soil nutrients (P, K, Fe, Mn, Cu, and Zn) that were tested are also significantly higher in amended versus unamended soils (Table 3). High levels of the metals Cu and Zn appear to be associated with biosolids application and not the wood waste as indicated by significant differences between plots with and without wood waste.

Long-term responses of vegetation to biosolids are somewhat different from those reported in the early years of the experiment (Sabey et al. 1981). Observations during the first few years after biosolids application indicated that shrub (the dominant component in undisturbed areas) biomass and cover were reduced in the high-application plots relative to control plots. Our long-term data indicate that shrubs as a group had less biomass in amended plots on subsoil substrate relative to controls and that the dominant shrub in this system, sagebrush (*Artemisia tridentata*), was absent on amended subsoil plots (Table 4). However, on the topsoil plots, shrub relative biomass was greatest in amended plots largely due to increased relative biomass of Fourwing saltbush (*Atriplex canescens*). Sagebrush was also absent on amended topsoil plots.

Perennial grasses, especially those that were part of the seed mix (Table 1), continue to dominate the study plots (Table 4). In our 2001 sampling, within the subsoil plots, perennial grasses were more dominant in the plots receiving more biosolids. However, in the topsoil plots, perennial grasses were less dominant in plots that received the highest biosolids application rate.

Subsoil plots contained more plant taxa than topsoil plots in 2001 (Table 4). Within the subsoil plots, there was a significant reduction in plant species diversity with increasing biosolids application rate.

The reference area was dominated by Big sagebrush (52% relative biomass) with a large perennial grass component (28% relative biomass) (Table 4). None of the experimental plots appeared to have a species composition similar to that of the reference area.

Table 2. Life-history groupings of plant taxa encountered in study plots and an adjacent undisturbed reference area during the summer of 2001.

Life History	*Taxa**
Annual grass	*Bromus tectorum* L.
Annual forb	*Alyssum alyssoides* (L.) L.; *Descurainia pinnata* (Walt.) Britt.; *Descurainia sophia* (L.) Webb ex Prantl; *Gaura mollis* James; *Lappula occidentalis* (S. Wats.) Greene var. *occidentalis*; *Lepidium perfoliatum* L.; *Packera multilobata* (Torr. & Gray ex Gray) W.A. Weber & A. Löve; *Phaseolus acutifolius* Gray; *Townsendia incana* Nutt.
Biennial forb	*Machaeranthera canescens* (Pursh) Gray ssp. *canescens* var. *canescens*; *Melilotus officinalis* (L.) Lam.; *Tragopogon dubius* Scop.
Perennial grass	*Agropyron cristatum* (L.) Gaertn.; *Agropyron desertorum* (Fisch. ex Link) J.A. Schultes; *Bromus inermis* Leyss.; *Elymus elymoides* (Raf.) Swezey; *Elymus lanceolatus* (Scribn. & J.G. Sm.) Gould ssp. *lanceolatus*; *Elymus trachycaulus* (Link) Gould ex Shinners ssp. *trachycaulus*; *Festuca trachyphylla* (Hack.) Krajina; *Koeleria macrantha* (Ledeb.) J.A. Schultes; *Nassella viridula* (Trin.) Barkworth; *Pascopyrum smithii* (Rydb.) A. Löve; *Poa pratensis* L.; *Poa secunda* J. Presl; *Sporobolus cryptandrus* (Torr.) Gray; *Thinopyrum intermedium* (Host) Barkworth & D.R. Dewey
Perennial forb	*Astragalus cicer* L.; *Erigeron engelmannii* A. Nels.; *Linum lewisii* Pursh; *Machaeranthera grindelioides* (Nutt.) Shinners var. *grindelioides*; *Pedicularis parryi* Gray; *Phlox hoodii* Richards. ssp. *muscoides* (Nutt.) Wherry; *Sphaeralcea coccinea* (Nutt.) Rydb.; *Tetraneuris acaulis* (Pursh) Greene
Shrubs	*Artemisia tridentata* Nutt.; *Atriplex canescens* (Pursh) Nutt.; *Chrysothamnus viscidiflorus* (Hook.) Nutt.; *Ephedra viridis* Coville; *Ericameria nauseosa* (Pallas ex Pursh) Nesom & Baird ssp. *nauseosa* var. *nauseosa*; *Gutierrezia sarothrae* (Pursh) Britt. & Rusby; *Krascheninnikovia lanata* (Pursh) A.D.J. Meeuse & Smit; *Tetradymia canescens* DC.

*Nomenclature follows USDA Plants Database (USDA & NRCS 2004).

Table 3. Results of measured soil variables in the summer of 2001.

			Substrate							
			Subsoil				*Topsoil*			
	Depth	*BS[a] (Mg/ha):*	*0*	*56*	*112*	*224*	*0*	*56*	*112*	*224*
Variable	*(cm)*	*WW[b] (Mg/ha):*	*0*	*0*	*22.4*	*44.8*	*0*	*0*	*22.4*	*44.8*
pH	0–2.5		7.83a	7.63b	7.53b	7.57b	7.77A	7.70AB	7.73AB	7.63B
	0–15		7.97a	7.87ab	7.80b	7.80b	7.90A	7.87A	7.77B	7.77B
Electrical conductivity	0–2.5		0.50b	0.60a	0.50b	0.50b	0.60	0.60	0.57	0.57
(mmhos/cm)	0–15		0.47	0.53	0.57	0.53	0.43B	0.50AB	0.53A	0.57A
Organic matter (%)	0–2.5		1.97c	3.73b	6.27a	7.13a	2.47B	3.83B	5.50AB	8.87A
	0–15		1.10b	1.67b	2.60a	2.93a	1.60C	2.17C	3.40B	4.30A
NO_3^--N (Mg/kg)	0–2.5		4.10b	5.77a	5.63a	5.27ab	3.50B	3.80AB	5.77AB	6.23A
	0–15		3.67	4.37	4.20	4.40	2.67B	2.93B	3.23B	4.60A
C:N	0–2.5		23.56a	14.45b	10.83b	11.06b	15.70A	13.21AB	12.23AB	8.85B
	0–15		40.78a	24.61b	18.66b	16.70b	18.47	14.85	12.25	17.12
P (Mg/kg)	0–2.5		17.07c	47.40b	94.00a	100.67a	15.60C	24.27BC	54.50AB	75.60A
	0–15		10.83c	24.17bc	39.50b	62.00a	6.57C	18.13C	34.83B	49.97A
K (Mg/kg)	0–2.5		280.67b	462.33a	365.00ab	382.67a	449.33	529.00	593.33	612.00
	0–15		220.33ab	300.33a	199.67b	262.00ab	266.00	230.33	255.33	352.00
Fe (Mg/kg)	0–2.5		6.15b	23.50b	59.97a	66.17a	5.94C	11.69BC	28.17AB	41.43A
	0–15		4.65b	12.10b	26.53a	28.40a	4.49D	13.20C	26.10B	34.70A
Mn (Mg/kg)	0–2.5		5.89c	9.04b	10.53a	10.67a	7.84	8.61	9.69	11.40
	0–15		3.12b	4.17b	5.36a	5.66a	3.33B	3.66B	5.78A	6.05A
Zn (Mg/kg)	0–2.5		1.70b	21.20b	78.63a	90.47a	1.31B	8.62B	33.27AB	67.23B
	0–15		0.92b	8.25b	24.87a	27.60a	1.11C	9.02C	27.43B	41.00A
Cu (Mg/kg)	0–2.5		3.04b	25.57b	79.90a	85.70a	2.74C	11.55BC	38.80AB	63.20A
	0–15		1.80b	11.66b	28.73a	32.57a	2.78D	14.60C	30.07B	44.53A

Means for each substrate within a row followed by different letters are significantly different ($p < 0.05$, Fisher's LSD, $n = 3$).
[a] Biosolids.
[b] Wood waste.

Table 4. Relative biomass (%) of various groups of plant species in the summer of 2001 in amended study plots and an adjacent undisturbed reference area.

	Substrate								
	Subsoil				*Topsoil*				*Reference Area*
BS[a] *(Mg/ha):*	*0*	*56*	*112*	*224*	*0*	*56*	*112*	*224*	*0*
WW[b] *(Mg/ha):*	*0*	*0*	*22.4*	*44.8*	*0*	*0*	*22.4*	*44.8*	*0*
Annual grass	0.28	0.53	0.06	0.08	0.00	0.04	0.01	0.68	0.35
Annual forb	1.22	0.35	2.98	0.53	0.01	0.11	3.41	1.59	0.54
Biennial forb	0.93	0.21	0.00	0.10	0.11	0.10	0.00	0.00	0.00
Perennial grass	52.31b	81.23ab	78.82ab	89.82a	94.46A	91.37A	82.10AB	72.14B	27.78
Perennial forb	7.25a	0.64b	0.00b	0.56b	0.13	0.00	0.00	0.00	5.72
Shrub	37.94	16.95	18.14	8.91	5.30B	8.37B	14.48AB	25.59A	65.62
Artemisia tridentata	12.30a	0.00b	0.00b	0.00b	1.32	0.00	0.00	0.00	52.28
Atriplex canescens	0.56	8.32	5.81	5.63	2.86B	8.16B	13.83AB	24.81A	8.93
Seeded species	43.21	52.03	47.55	30.91	93.04	99.34	95.93	94.36	NS[c]
Aboveground biomass (g/m^2)	125.10	124.19	123.85	177.24	116.97B	184.42A	173.77AB	141.42AB	131.69
Number of taxa	18.00a	13.67b	8.33c	9.67c	7.00	5.00	4.67	5.67	22.00

Means for each substrate within a row followed by different letters are significantly different ($p < 0.05$, Fisher's LSD, $n = 3$).
[a] Biosolids.
[b] Wood waste.
[c] Not seeded.

Discussion

Results after the first 3 years of this study led the original investigators to conclude that biosolids had positive effects on overall plant growth by lowering pH and by supplying phosphorus, trace elements, and organic matter to the disturbed soils (Sabey et al. 1981). The biosolids amendments favored grasses but had a negative impact on shrubs. Our results, obtained 24 years after biosolids treatment application, indicate that the originally reported effects on soil parameters continue to be evident, especially on the lower-fertility subsoil plots. There were also significant long-term effects of biosolids on plant community structure, but these effects vary between the low-fertility subsoil plots and the higher-fertility topsoil plots.

Twenty-four years after biosolids application, soil pH was still significantly lower on plots receiving biosolids or biosolids plus wood waste. The mechanism by which the amendments have reduced pH is not evident from the results of this study, but it is likely that increased organic acids and soil microbial activity associated with increased organic matter have contributed. Associated with the reduced pH and increased organic matter in the biosolids plots was a lower C-to-N ratio. A lower C-to-N ratio indicates that microbially mediated nutrient cycling is likely to be more favorable in biosolids-amended plots. The lower C-to-N ratio in the biosolids-amended plots may, in part, be due to the use of a highly stable form of biosolids in this study. Greater amounts of nitrate in amended plots versus unamended plots suggest that amended soils with low C-to-N ratios and lower pH continue to supply plants with more available N. These results are consistent with other studies using biosolids in semiarid systems where improvements in soil fertility were associated with elevated soil organic matter and carbon from biosolids (Pierce et al. 1998; Navas et al. 1999).

These results suggest that increased soil fertility in the amended plots is a continuing legacy of the biosolids application, even 24 years after application. Altered soil fertility appears to still be controlling development of the plant community. A subsequent study at the Piceance Basin site found that soil P had little or no effect on plant community development following disturbance, whereas soil N availability was strongly linked with secondary succession (McLendon & Redente 1991), with higher soil mineral N promoting the dominance of early-seral weedy annual species. These findings suggest that significantly higher levels of soil P found in amended plots in this study do not explain observed differences in the plant communities. However, the effects of biosolids on N cycling may have had a strong influence on plant community development.

Continued elevated levels of Cu and Zn in amended plots might also be affecting the plant community. We did not assess plant uptake of metals in this study, but we have noted Zn toxicity to some native grass species within the range of soil Zn encountered in this study (Paschke et al. 2000). Metal toxicity from high levels of biosolids application has been noted for some agronomic plant species (Berti & Jacobs 1996).

Other long-term studies at the Piceance Basin site have found that seed mixture composition has a lasting effect on plant community composition (Sydnor & Redente 2000; Newman & Redente 2001). Our results suggest that this is especially true for soils with high initial fertility (topsoil plots) where seeded grasses may quickly establish and dominate the site. Competition from seeded grasses on all plots appears to have slowed secondary succession toward a more shrub-dominated community as is found in the reference area. The dominant shrub species in the reference area, Big sagebrush, was not encountered on amended topsoil or subsoil plots in 2001.

Our finding that high levels of biosolids amendments to nutrient-poor soils promote grasses over other life forms is similar to that of Rigueiro-Rodriguez et al. (2000), who reported that biosolids promoted pasture grasses and reduced tree growth in northwestern Spain. At other sites in Colorado, we have noted similar grass dominance at nutrient-poor sites receiving high levels of biosolids (Pierce et al. 1998; Meyer et al. 2004).

The use of increasing levels of biosolids on a low-fertility (subsoil) substrate in this study was associated with a lasting increase in soil fertility, which was associated with a reduction in plant species diversity and dominance by perennial grasses. Effects of biosolids on soil fertility were not as pronounced on a higher-fertility (topsoil) treatment, where increasing levels of biosolids were associated with a decrease in perennial grass dominance and an increase in shrub dominance. If the goal of restoration is to restore a sagebrush steppe community (similar to the reference area), then the use of biosolids in this study can thus be viewed as having an initial positive effect on nutrient-poor soils in the short term (Sabey et al. 1981) but a negative effect on nutrient-poor soils in the long term. However, the use of biosolids on nutrient-rich soil can be viewed as having an initial negative effect on restoration of sagebrush steppe (Sabey et al. 1981) but a positive effect in the longer term. It is important to note how goals of restoration have generally changed during the course of this long-term study in that current projects often strive to establish native late-seral communities, whereas in past decades the goals of restoration were often more directed at establishing vegetative cover.

Remaining questions associated with this study include the following: Is plant community development controlled by biosolids promoting some plant species over others through elevated soil fertility? Or is plant community development controlled by potential metal toxicity from biosolids to key species such as sagebrush?

Conclusion

Based on these long-term results, it appears that the use of biosolids for sagebrush steppe restoration should be considered carefully. If the long-term goal of restoration is reestablishment of native sagebrush steppe, then lesser amounts of biosolids than used in this study should be considered. The use of persistent perennial grass species in seed mixes may slow the establishment of shrub species where the grasses are benefiting from high soil fertility. Seed mixtures should be designed in such a way as to reduce this competitive advantage that grasses have over shrubs.

LITERATURE CITED

Berti, W., and L. Jacobs. 1996. Chemistry and phytotoxicity of soil trace elements from repeated sewage sludge applications. Journal of Environmental Quality **25:**1025–1032.

Ippolito, J. A., K. A. Barbarick, and E. F. Redente. 1999. Co-application effects of water treatment residuals and biosolids on two range grasses. Journal of Environmental Quality **28:**1644–1650.

Ippolito, J. A., K. A. Barbarick, and E. F. Redente. 2002. Combinations of water treatment residuals and biosolids affect two range grasses. Communications in Soil Science and Plant Analysis **33:** 831–844.

McLendon, T., and E. F. Redente. 1991. Nitrogen and phosphorus effects on secondary succession dynamics on a semi-arid sagebrush site. Ecology **76:**2016–2024.

Meyer, V. F., E. F. Redente, K. A. Barbarick, and R. Brobst. 2001. Biosolids applications affect runoff water quality following forest fire. Journal of Environmental Quality **30:**1528–1532.

Meyer, V. F., E. F. Redente, K. A. Barbarick, R. B. Brobst, M. W. Paschke, and A. L. Miller. 2004. Plant and soil responses to biosolids application following forest fire. Journal of Environmental Quality **33:**873–881.

Navas, A., J. Machin, and B. Navas. 1999. Use of biosolids to restore the natural vegetation cover on degraded soils in the badlands of Zaragoza (NE Spain). Bioresource Technology **69:**199–205.

Newman, G. J., and E. F. Redente. 2001. Long-term plant community development as influenced by revegetation techniques. Journal of Range Management **54:**717–724.

Paschke, M. W., E. F. Redente, and D. B. Levy. 2000. Zinc toxicity thresholds for important reclamation grass species of the western United States. Environmental Toxicology and Chemistry **19:** 2751–2756.

Pierce, B. L., E. F. Redente, K. A. Barbarick, R. B. Brobst, and P. Hegeman. 1998. Plant biomass and elemental changes in shrubland forages following biosolids application. Journal of Environmental Quality **27:**789–794.

Rigueiro-Rodriguez, A., M. R. Mosquera-Losada, and E. Gatica-Trabanini. 2000. Pasture production and tree growth in a young pine plantation fertilized with inorganic fertilizers and milk sewage in northwestern Spain. Agroforestry Systems **48:**245–256.

Sabey, B. M., M. K. Corwin, and T. B. Doerr. 1981. Long-term fertility study on land drastically disturbed by oil shale development. Pages 57–68 in E. F. Redente, and C. W. Cook, editors. Revegetation research on oil shale lands in the Piceance Basin. Progress Report for US Department of Energy DE-AS02-76EV-4018. Colorado State University, Department of Range Science, Fort Collins.

Sort, X., and J. M. Alcaniz. 1996. Contribution of sewage sludge to erosion control in the rehabilitation of limestone quarries. Land Degradation & Development **7:**69–76.

Sydnor, R. S., and E. F. Redente. 2000. Long-term plant community development on topsoil treatments overlying a phytotoxic growth medium. Journal of Environmental Quality **29:**1778–1786.

USDA (U.S. Department of Agriculture). 1982. Soil survey of the Rio Blanco County area, Colorado. USDA. U.S. Government Printing Office, Washington, D.C.

USDA (U.S. Department of Agriculture), and NRCS (Natural Resources Conservation Service). 2004. The PLANTS Database, version 3.5 (available from http://plants.usda.gov). National Plant Data Center, Baton Rouge, Louisiana.

Zebarth, B. J., R. McDougall, G. Neilsen, and D. Neilsen. 2000. Availability of nitrogen from municipal biosolids for dryland forage grass. Canadian Journal of Plant Science **80:**575–582.