Soil Nitrate Nitrogen Dynamics after Biosolids Application in a Tobosagrass Desert Grassland

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ABSTRACT

Dormant-season application of biosolids increases desert grass production more than growing season application in the first growing season after application. Differential patterns of NO_3–N (plant available N) release following seasonal biosolids application may explain this response. Experiments were conducted to determine soil nitrate nitrogen dynamics following application of biosolids during two seasons in a tobosagrass [*Hilaria mutica* (Buckl.) Benth.] Chihuahuan Desert grassland. Biosolids were applied either in the dormant (early April) or growing (early July) season at 0, 18, or 34 dry Mg ha^{-1}. A polyester–nylon mulch was also applied to serve as a control that approximated the same physical effects on the soil surface as the biosolids but without any chemical effects. Supplemental irrigation was applied to half of the plots. Soil NO_3–N was measured at two depths (0–5 and 5–15 cm) underneath biosolids (or mulch) and in interspace positions relative to surface location of biosolids (or mulch). Dormant-season biosolids application significantly increased soil NO_3–N during the first growing season, and also increased soil NO_3–N throughout the first growing season compared to growing-season biosolids application in a year of higher-than-average spring precipitation. In a year of lower-than-average spring precipitation, season of application did not affect soil NO_3–N. Soil NO_3–N was higher at both biosolids rates for both seasons of application than in the control treatment. Biosolids increased soil NO_3–N compared to the inert mulch. Irrigation did not significantly affect soil NO_3–N. Soil NO_3–N was not significantly different underneath biosolids and in interspace positions. Surface soil NO_3–N was higher during the first year of biosolids application, and subsurface soil NO_3–N increased during the second year. Results showed that biosolids rate and season of application affected soil NO_3–N measured during the growing season. Under dry spring–normal summer precipitation conditions, season of application did not affect soil NO_3–N; in contrast, dormant season application increased soil NO_3–N more than growing season application under wet spring–dry summer conditions.

PLANT GROWTH in arid and semiarid environments is limited by soil water and nutrients. In the southwestern United States, soil fertility can be improved by application of organic wastes (Khaleel et al., 1981; Fuller, 1991). Sewage sludge is a term that describes the untreated residue (solid, semisolid, or liquid) that is generated during the treatment of domestic sewage. Sewage sludge can be further treated (e.g., through anaerobic digestion) for pathogen control. Biosolids, a term that describes treated sewage sludge, are an organic waste recommended for land application by the USEPA (1989).

Biosolids application at low to moderate (5–80 dry Mg ha^{-1}) rates in rangelands, although not common yet, has beneficial effects on soil and vegetation. A pioneer study (Fresquez et al., 1990) reported favorable effects on soil and plant properties following biosolids application in a degraded semiarid rangeland in New Mexico. Aguilar et al. (1994) also showed favorable effects of surface-applied biosolids at 45 dry Mg ha^{-1} on some soil properties, forage production, and quality of blue grama [*Bouteloua gracilis* (H.B.K.) Lag. ex Steud] in a semiarid rangeland in New Mexico. In Colorado, Pierce et al. (1998) found increases (up to 300%) in biomass and plant tissue nitrogen (up to 60–70%) of three cool season grasses with biosolids applied at rates up to 40 dry Mg ha^{-1}.

Recent research shows favorable effects of biosolids application on Chihuahuan Desert grassland soils (Rostagno and Sosebee, 2001; Moffet et al., 2005), and forage production of alkali sacaton [*Sporobolus airoides* (Torr.) Torr.] (Benton and Wester, 1998) and tobosagrass (Benton and Wester, 1998; Jurado and Wester, 2001). Martínez et al. (2003) reported beneficial effects of biosolids application on soil N, P, and K, and increases in plant canopy and biomass in a degraded semiarid Mediterranean ecosystem. Surface-applied biosolids can also enhance seedling establishment under moderate environmental conditions (Hahm and Wester, 2004).

Favorable effects on plant growth may be explained by potential physical and chemical effects of biosolids on soil properties. Surface-applied biosolids affect soil temperature extremes and moderate fluctuations in soil temperature; biosolids also affect soil moisture dynamics (Hahm and Wester, 2004). Because semiarid regions are water limited, and may be nutrient limited as well, an increase in soil water or nutrients will favor plant growth. Nitrogen is the most limiting nutrient for plant growth in rangelands (Barbour et al., 1987; Holechek et al., 1989); nitrate nitrogen concentration is more highly correlated with forage yields than total N in rangelands (Vallentine, 1989). Organic nutrient release following biosolids amendment is slow, with high potential for nutrient mineralization (Chae and Tabatabai, 1986; Barbarick et al., 1996; Beltrán-Hernández et al., 1999). Little information is available on soil N availability during the plant growing season following biosolids application in rangeland ecosystems.

Biosolids application in the Trans-Pecos of Texas during the dormant season (January–April) of perennial grasses promoted greater forage yields of tobosagrass

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Abbreviations: IM, inert mulch.

(Benton and Wester, 1998; Jurado and Wester, 2001; Mata-González et al., 2002), alkali sacaton (Benton and Wester, 1998), and blue grama (Mata-González et al., 2002) compared to the growing season (July) application. This response may be related to the longer residence time of biosolids applied in the dormant season (Benton and Wester, 1998). However, this seasonal effect needs to be investigated to more fully understand the potential nutrient release of seasonal application of biosolids in semiarid rangelands. In this study, we tested the hypothesis that soil NO_3–N release patterns throughout the growing season in a tobosagrass desert grassland site are not affected by rate or season of biosolids application, or supplemental irrigation. Surface-applied biosolids affect microenvironmental conditions abiotically through effects on soil temperature and soil water; biosolids, however, also have chemical effects through nutrient release. We used biosolids as well as an inert mulch (that simulated the physical effects of biosolids without confounding chemical effects) to separate abiotic and chemical effects of biosolids.

MATERIALS AND METHODS

Study Area

Research was conducted on the Sierra Blanca Ranch in the northern Chihuahuan Desert in the Trans-Pecos of Texas. Climate is a southwestern type characterized by hot summers (June through August) and cool winters (November through February). Summer precipitation occurs as convectional storms with high intensity and short duration (Holechek et al., 1989). Annual long-term precipitation ranges from 150 to 300 mm with 65% occurring between July and September (NOAA, 1993).

The study site is a grassland dominated by tobosagrass and alkali sacaton. Honey mesquite (*Prosopis glandulosa* var. *glandulosa* Torr.) and lotebush [*Ziziphus obtusifolia* (T.&G.) Gray] are scattered throughout this Loamy (variant) Range Site (Wester and Benton, unpublished data). Soils of the study area occur on planar slopes of the lower part of an alluvial fan. The soil is deep, with high water holding capacity, low permeability, and is tentatively classified as a taxadjunct of the Stellar series (Casby-Horton, 1997). The Stellar series is a fine, mixed, superactive, thermic, Ustic Calciargid. The soil profile at the study site is calcareous throughout. The surface horizon overlies argillic and calcic horizons. The A horizon (0–7 cm) is a very fine sandy loam, dark yellowish brown 10YR 3/4 moist, platy structure with many fine and medium roots. The Bt1 horizon (7–33 cm) is a clay, brown (7.5YR 4/4) moist, blocky and subangular blocky structure with many fine and medium roots (Casby-Horton, 1997). The site has been excluded from grazing by domestic livestock since 1992.

Plot Establishment and Biosolids Application

Ninety hexagonal field plots (4.19 m^2) similar in coverage of bare soil and vegetation were selected. Six metal bars and aluminum flashing (10 cm tall) were used to shape plots and enclose applied mulches. A central, vegetated 0.5-m^2 subplot in the center of the plot was used for vegetation sampling; the remainder of the plot was used for soil sampling. Initial soil samples of the A (0–5 cm) and Bt1 (5–15 cm) horizons were collected from all experimental plots in March 1997 before the biosolids application to obtain baseline information. After initial soil samples were collected, vegetation in the plot area to be used for soil sampling was trimmed to ground level with a weed eater and at the beginning of the growing season was treated with glyphosate herbicide to kill vegetation and eliminate nitrogen uptake by plants.

An organic mulch (New York City dewatered, municipal, anaerobically digested biosolids, supplied by a local commercial biosolids applicator) was applied to experimental plots once a year in 1997 or 1998. Biosolids were applied in the dormant season (early April) or at the onset of the growing season (early July) in 1997 and 1998. An inert, porous mulch (IM) made of nylon and polyester fibers (by 3M Corporation, Minneapolis, MN), with a density of 0.1094 g cm^{-3} and 1.87 cm thick, was cut into small pieces of random shapes and applied to simulate the physical effects of biosolids. That is, the IM had a dark color similar to dried biosolids, and laboratory experiments indicated that the water-holding capacity of the IM (82% water adsorption) was similar to that of biosolids (78% water adsorption). For each season of application, five biosolids samples were randomly collected before application and immediately frozen for future chemical analysis at the SWAT laboratory at New Mexico State University. Five biosolids samples were collected 24 h before application, and moisture was determined by oven-drying samples at 60°C for 24 h.

Three biosolids rates (0, 18, or 34 Mg ha^{-1}) were applied to experimental plots on a dry-weight basis. Fresh biosolids were weighed in the field, and uniformly distributed in each plot with a rake. The IM was applied at the onset of the growing season (early July) in 1997 to provide a soil cover similar to that of dry biosolids applied at 18 Mg ha^{-1} (27% cover) or 34 Mg ha^{-1} (52% cover) (soil cover values were determined previously in 1-yr-old biosolids-treated plots from related research projects). Half of the plots received supplemental irrigation at a rate of 15 mm of water approximately biweekly from July to August 1997 (75 mm total applied), to produce a response in the event of a drought during the growing season.

Soil Sampling

Three surface (0- to 5-cm depth) and three subsurface (5- to 15-cm depth) soil samples were collected with a 2-cm-diameter soil probe in each experimental plot 2 d after irrigation; the three samples from each location and sampling date were composited. In treated plots, soil samples were collected underneath biosolids (or mulch) (underneath position), and between biosolids (or mulch) (interspace position) or bare soil. In control plots, soil samples were collected in bare soil.

Soil samples were placed in plastic bags and stored in an ice chest in the field; thereafter, samples were refrigerated at 4°C for 24 h to slow biological activity, air-dried for 48 h at room temperature (21°C; Maynard and Kalra, 1993; Mulvaney, 1996), and stored under cool, dry conditions for subsequent chemical analysis. Soil samples were collected monthly from June to August 1997. After soil sampling, holes in each plot were back-filled with next-to-plot dry soil to reduce soil disturbance and marked to avoid resampling of the same location. Soil samples were sieved to pass through a 2-mm screen, and ground with mortar and pestle before chemical analysis. Nitrate nitrogen was determined in soil samples, including initial samples, within 3 mo after collection, by extraction of nitrate with KCl, followed by Cd reduction and a colorimetric technique (Mulvaney, 1996) with a digital spectrophotometer (DR/2000; Hach, Loveland, CO).

In 1998, 120 new plots (same size and shape as in 1997) were established; this experiment allowed for replication in time of first-year effects of biosolids and IM. Dormant-season application of IM was included in the 1998-treated plots. The same measurements of soil NO_3–N were recorded in 1998-treated plots. Carry-over effects of biosolids and IM were assessed throughout the second year of the study in 1998 by measuring soil NO_3–N in plots established in 1997. That is, data were collected in 1997 and 1998 from plots established in 1997, and only in 1998 for plots established in 1998. Monthly precipitation data during the two years of the study were recorded by rain gauges on site.

Experimental Design and Data Analyses

A split plot arrangement of a completely randomized design was used for this study, with a factorial combination of three mulch rates and two irrigation levels randomly applied in the main plot portion of the experiment, with five replications of each mulch rate–irrigation combination. A factorial combination of two seasons of application and two mulch types was randomly assigned to experimental plots in the subplot for every combination of rate and irrigation. In 1997, there were 3 rates of biosolids application, 2 levels of irrigation, 2 seasons of application, and 5 replications, for a total of 60 plots; also, there were 3 rates of inorganic mulch, 2 levels of irrigation, and 5 replications, for a total of 30 plots. In 1997, only season or mulch was used as a subplot factor. Soil sample position, soil depth, and date of soil sampling were used as repeated measurements in the analyses of variance. In 1998, for both biosolids and inorganic mulch, there were 3 rates of application, 2 levels of irrigation, 2 seasons of application, and 5 replications, for a total of 120 plots. The Shapiro–Wilk (Shapiro and Wilk, 1965) test was used to assess normality of errors in the main plot and in all subplot experimental error terms. Homogeneity of variances in the main plot was assessed with the Levene's (1960) test. Mauchly's (1940) test was used to test for sphericity in all subplots portions of the analysis of variance. Normality and/or sphericity was violated for one or more errors terms in the analysis of variance for both years of data; thus, data were analyzed on a natural log-transformed scale, and back-transformed treatment means (estimates of medians on the observed scale; Jagger and Looman, 1987) are presented. Significant effects were determined with Greenhouse–Geisser adjusted *F* tests when the sphericity assumption was violated (Kirk, 1995). Mean separation was performed with the Fisher's Least Significant Difference (LSD) test (Steel and Torrie, 1980) to determine differences among treatments for significant effects. When interaction between factors was significant, simple main effects were tested, followed by simple effect tests, using appropriate error terms and degrees of freedom. Separate error terms were used for mean separation when sphericity was violated (Kirk, 1995). A probability level of 5% was used for analysis of variance and mean separation.

RESULTS

Annual precipitation in the study area was below the long-term average (303 mm) in 1997 (245 mm) and 1998 (221 mm) (Fig. 1). Precipitation was above the long-term average during the spring of 1997, but below long-term in the spring of 1998. Chemical composition of biosolids is shown in Table 1. Overall, biosolids used in this research were similar in composition to biosolids used in related work (e.g., Benton and Wester, 1998; Jurado and Wester, 2001; Wester et al., 2003).

Results for field plots treated in 1997 will be discussed below as follows: since biosolids were applied in both seasons, but IM was applied only in the growing season, statistical analyses include comparisons of seasons of application for biosolids-treated plots, and comparisons of mulches for plots treated with biosolids and IM in the growing season. For plots established in 1998, statistical analyses included comparisons of both seasons and mulches simultaneously.

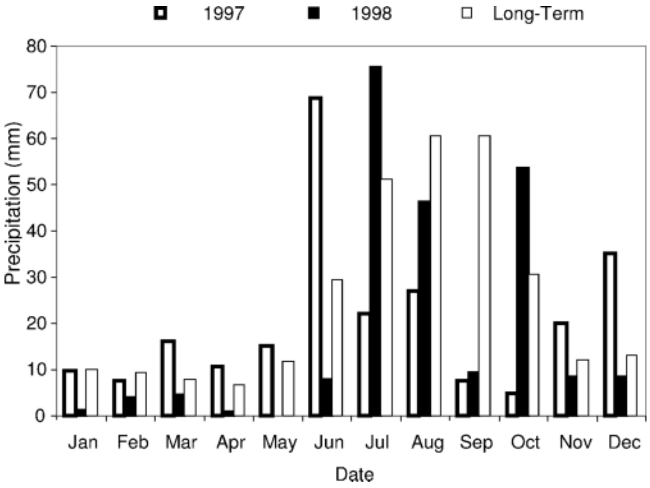

Fig. 1. Monthly precipitation at the Stellar/Tobosagrass Site (ST) in 1997 and 1998, and long-term monthly precipitation (NOAA, 1993) in Sierra Blanca, TX.

Field Experiment, 1997

Initial analysis of soil samples from March 1997 indicated that NO_3–N was not significantly different among treatments before mulch application. An average of 5.3 mg kg^{-1} of soil NO_3–N was observed in experimental

Table 1. Chemical analyses (dry-weight basis) of biosolids applied to study sites in 1997 and 1998, Sierra Blanca, TX.

	Season and year of biosolids application†			
Parameter	Dormant, 1997	Growing, 1997	Dormant, 1998	Growing, 1998
Moisture, %	77.2	76.4	77.8	75.0
OM‡, %	NM§	NM	31.59	33.60
TKN¶, %	4.01	2.34	4.53	3.48
NO_3–N, mg kg^{-1}	NM	NM	42.20	30.20
NH_4–N, mg kg^{-1}	NM	NM	6617	5524
P, %	1.98	1.77	2.79	2.23
K, %	0.10	0.11	0.13	0.11
Ca, %	2.25	2.06	2.14	2.19
Mg, %	0.67	0.53	0.87	0.86
S, %	1.49	1.52	1.39	1.88
Na, %	0.11	0.10	0.03	0.24
Zn, mg kg^{-1}	1031	1096	917	1089
B, mg kg^{-1}	23.40	20.80	12.20	16.00
Fe, mg kg^{-1}	14260	22116	51974	11731
Mn, mg kg^{-1}	1192	386	1225	1131
Cu, mg kg^{-1}	938	911	818	839
Al, mg kg^{-1}	9255	10365	7549	9236
Ni, mg kg^{-1}	31	88	19	18
Cd, mg kg^{-1}	6	BDL#	3	BDL
Pb, mg kg^{-1}	216.00	224.94	217.66	252
EC†† dS m^{-1}	7	8	8	16

† Dormant, 1997 = biosolids applied in the dormant season in 1997; Growing, 1997 = biosolids applied in the growing season in 1997; Dormant, 1998 = biosolids applied in the dormant season in 1998; Growing, 1998 = biosolids applied in the growing season in 1998; *n* = 5 for all seasons of biosolids application.

‡ Organic matter.

§ Not measured.

¶ Total Kjeldahl nitrogen.

Below detection limit (1 mg kg^{-1}).

†† Electrical conductivity.

plots regardless of soil depth. Hence, significant effects on soil NO_3–N after this date can be attributed to mulch application.

A biosolids rate × season of application × soil depth × date of sampling interaction affected soil NO_3–N ($P < 0.0019$, Fig. 2). In June 1997, surface soil NO_3–N significantly increased at both the 18 and 34 Mg ha^{-1} rates applied in the dormant season compared to the control rate. Subsurface soil NO_3–N was not significantly different among biosolids rates regardless of season of application on this date. For all following sampling dates, including July 1998, surface and subsurface soil NO_3–N significantly increased at both biosolids rates compared to the control treatment in both seasons of biosolids application (Fig. 2). Additionally, a significantly greater effect on soil NO_3–N was observed under dormant season application of biosolids than under growing season application of biosolids in both rates regardless of soil depth on most sampling dates (Fig. 2).

During the first year following treatment, NO_3–N in the surface soil was significantly increased compared to the subsurface soil regardless of season of biosolids application. In the second year following treatment (July 1998), a reverse effect was observed in soil NO_3–N (Table 2).

A biosolids rate × irrigation × soil depth × date of sampling interaction also affected soil NO_3–N ($P < 0.0004$, Table 3). Irrigation began in early July 1997. Soil NO_3–N was not significantly different under irrigated and nonirrigated conditions regardless of biosolids rate and soil

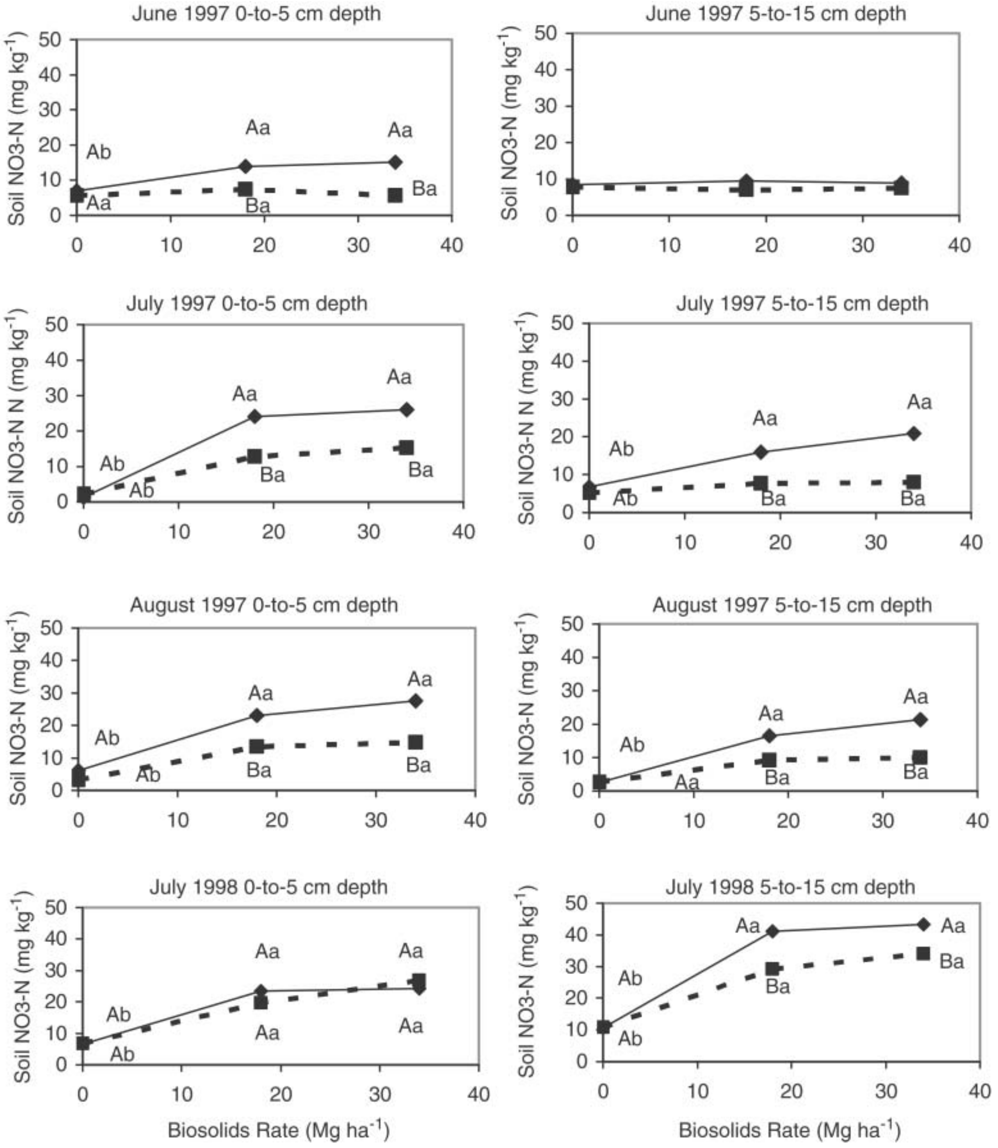

Fig. 2. Soil NO_3–N (mg kg^{-1}) in a Stellar soil as affected by biosolids rate, season of biosolids application, soil depth, and sampling date in 1997 and 1998. Biosolids were applied in 1997. Rate means within a season of application followed by the same lowercase letter are not significantly different ($P > 0.05$). Season of application means within a rate followed by the same uppercase letter are not significantly different ($P > 0.05$); $n = 10$. Figures lacking mean separation letters indicate corresponding nonsignificant effects. Solid lines represent biosolids application in the dormant season; dashed lines represent biosolids application in the growing season. Data are back-transformed means from natural log-transformed data.

Table 2. Soil NO_3–N in a Stellar soil as affected by biosolids rate, soil depth, season of biosolids application, and sampling date in 1997 and 1998, Sierra Blanca, TX. Biosolids were applied in 1997. Data are back-transformed means from natural log-transformed data.

Sampling date	Season of application	Soil depth	Rate (Mg ha^{-1}) 0	18	34	Mean
		cm	mg kg^{-1}			
June 1997	growing	0–5	5.6a†	7.4a	5.6a	6.2
		5–15	7.6b	6.9a	7.4b	10.9
	dormant	0–5	6.9a	13.9a	15.1a	11.9
		5–15	8.3a	9.4b	8.8b	8.8
July 1997	growing	0–5	2.2b	12.7a	15.2a	10.0
		5–15	5.2a	7.7b	7.9Bb	6.9
	dormant	0–5	1.4b	24.1a	26.0a	17.1
		5–15	6.7a	15.9b	20.8a	14.4
August 1997	growing	0–5	3.1	13.4	14.7	10.4A‡
		5–15	2.5	9.21	9.9	7.2B
	dormant	0–5	6.0a	23.1a	27.5a	18.8
		5–15	2.5b	16.5b	21.3b	13.4
July 1998	growing	0–5	6.7	19.6	26.7	17.6A
		5–15	10.7	29.1	34.0	24.6A
	dormant	0–5	6.6	23.5	24.1	18.0B
		5–15	10.6	41.0	43.3	31.6A

† Soil depth means at the same sampling date, season of application, and rate followed by the same lowercase letter are not significantly different ($P > 0.05$); $n = 10$.

‡ Soil depth means at the same sampling date and season of application followed by the same uppercase letter are not significantly different ($P > 0.05$).

depth on most sampling dates. Nitrate nitrogen contents were higher at 18 and 34 mg ha^{-1} than in control treatments, but generally not significantly different between rates of application (Table 3).

When comparing mulches, an interaction involving rate of application, irrigation, mulch type, soil depth, and sampling date influenced soil NO_3–N ($P < 0.0142$, Table 4). In general, surface soil NO_3–N significantly increased at both application rates compared to the control plots regardless of mulch type or irrigation on most sampling dates. However, a more pronounced effect was observed under biosolids than under IM application. Also, subsurface soil NO_3–N was significantly increased with biosolids and remained similar to IM regardless of irrigation on most sampling dates.

Field Experiment, 1998

For plots established in 1998, initial analysis of soil samples from February 1998 showed that NO_3–N was not significantly different among treatments before any mulch application. An average of 6.2 mg kg^{-1} of soil NO_3–N was observed in experimental plots regardless of soil depth. Hence, significant effects on soil NO_3–N after this date can be attributed to mulch application.

Soil NO_3–N was influenced by a rate × irrigation × season of application × mulch type × date of sampling interaction ($P < 0.0001$). In June 1998, the only significant effect was biosolids rate: biosolids applied in the dormant season significantly increased soil NO_3–N at both the 18 and 34 Mg ha^{-1} rates compared to the control rate (5.0 mg kg^{-1} of soil NO_3–N) under non-irrigated conditions; also, biosolids applied at 18 Mg ha^{-1} significantly increased soil NO_3–N (7.3 mg kg^{-1} of soil NO_3–N) compared to 34 Mg ha^{-1} (5.9 mg kg^{-1} soil NO_3–N). In August 1998, under non-irrigated conditions, soil NO_3–N was not significantly different between the control and 18 Mg ha^{-1} rates when biosolids were applied in the dormant season, and increased significantly at the 34 Mg ha^{-1} rate (Fig. 3). Further, soil NO_3–N increased significantly at both the 18 and 34 Mg ha^{-1} rates when biosolids were applied in the growing season (Fig. 3).

In August 1998, under irrigated conditions biosolids significantly increased soil NO_3–N in both seasons of application (Fig. 3). Additionally, a greater effect was observed in soil NO_3–N with dormant application of biosolids compared to growing season application at 34 Mg ha^{-1}. In plots under non-irrigated conditions there was no rate effect on soil NO_3–N with IM in any season of application (Fig. 3). Biosolids increased soil NO_3–N compared to IM at both the 18 and 34 Mg ha^{-1} rates in each season of application (Fig. 3). On plots with supplemental irrigation, biosolids increased soil NO_3–N compared to IM in both the 18 and 34 Mg ha^{-1} rates in each season of application. There was no rate effect on soil NO_3–N with IM application in any season of application (Fig. 3).

Mulch rate, irrigation, season of mulch application, mulch type, and soil depth interacted in their effects on soil NO_3–N ($P < 0.0133$) (Table 5). Comparisons of soil depths were made within rate, season, and mulch type. In plots under non-irrigated conditions and treated with biosolids in the dormant season, soil NO_3–N was not significantly different between depths in all rates (Table 5). When biosolids were applied in the growing season, subsoil NO_3–N was significantly higher compared to the surface soil in the control and 18 Mg ha^{-1} rates (Table 5). In contrast, soil NO_3–N was not significantly different between depths at the 34 Mg ha^{-1} rate. Soil NO_3–N was not significantly different between depths in all but one

Table 3. Soil NO_3–N in a Stellar soil as affected by biosolids rate, irrigation, soil depth, and sampling date in 1997 and 1998, Sierra Blanca, TX. Biosolids were applied in 1997. Data are back-transformed means from natural log-transformed data.

Sampling date	Soil depth	Irrigation	Rate (Mg ha^{-1}) 0	18	34	Mean
	cm		mg kg^{-1}			
July 1997	0–5	non-irrigated	2.9bA†	16.4aA	19.1aA	12.8
		irrigated	1.0bB	18.7aA	20.8aA	13.1
		mean	1.9	17.5	19.9	
	5–15	non-irrigated	5.6	9.8	12.2	9.2A
		irrigated	6.2	12.4	13.6	10.7A
		mean	5.9b	11.1a	12.9a	
August 1997	0–5	non-irrigated	4.8	16.0	17.6	12.8A
		irrigated	3.9	19.3	23.0	15.4A
		mean	4.4b	17.6a	20.3a	
	5–15	non-irrigated	3.0cA	9.7bB	13.3aA	8.7
		irrigated	2.1bA	15.6aA	15.8aA	11.2
		mean	2.5	12.7	14.5	
July 1998	0–5	non-irrigated	6.0	20.1	26.5	17.5A
		irrigated	7.3	22.9	24.3	18.2A
		mean	6.7b	21.5a	25.4a	
	5–15	non-irrigated	10.5	33.1	35.0	26.2A
		irrigated	10.8	36.6	42.2	29.8A
		mean	10.6b	34.8a	38.6a	

† Rate means within a sampling date, soil depth, and irrigation level followed by the same lowercase letter are not significantly different ($P > 0.05$). Irrigation means within a sampling date, soil depth, and rate followed by the same uppercase letter are not significantly different ($P > 0.05$); $n = 20$.

Table 4. Soil NO_3–N in a Stellar soil as affected by irrigation, soil depth, mulch, and rate in 1997 and 1998, Sierra Blanca, TX. Biosolids were applied in 1997. Data are back-transformed means from natural log-transformed data.

		Non-irrigated				Irrigated			
		Soil depth (cm)							
		0–5		5–15		0–5		5–15	
Sampling date	Rate	Biosolids	IM†	Biosolids	IM	Biosolids	IM	Biosolids	IM
	Mg ha^{-1}	mg kg^{-1}							
July 1997	0	4.8bA‡	1.6bB	5.9aA	10.5aA	1.0bB	2.2bA	4.6bA	6.2aA
	18	12.0aA	6.0aB	7.2aA	7.6aA	13.5aA	6.2aB	8.1aA	5.5aB
	34	14.3aA	6.9aB	7.3aA	7.5aA	16.3aA	6.7aB	8.6aA	5.0aB
August 1997	0	3.8bA	3.0bB	3.4bA	1.8bA	2.6bB	4.3bA	1.9bB	3.2bA
	18	12.7aA	6.5aB	7.4aA	6.8aA	14.1aA	6.1aB	11.3aA	5.6aB
	34	11.9aA	5.0aB	9.2aA	9.0aA	18.3aA	4.6abB	10.6aA	6.2aB
July 1998	0	5.7cA	5.5bA	11.2bA	10.7aA	7.9aA	7.9aA	10.2bA	13.2aA
	18	18.2bA	8.1aB	27.1aA	10.9aB	20.8aA	9.6aB	30.9aA	11.8aB
	34	28.3aA	9.0aB	31.2aA	12.5aB	25.2aA	11.7aB	37.1aA	12.0aB

† Inert mulch.

‡ Rate means within a mulch, soil depth, irrigation level, and sampling date followed by the same lowercase letter are not significantly different ($P > 0.05$). Mulch means within a rate, soil depth, irrigation level and sampling date followed by the same uppercase letter are not significantly different ($P > 0.05$); $n = 10$.

comparison under applications of IM (Table 5). Under irrigated conditions, subsoil NO_3–N was significantly higher compared to surface soil in control plots in most of the comparisons (Table 5). In contrast, surface soil NO_3–N significantly increased in both the 18 and 34 Mg ha^{-1} rates when biosolids were applied in the dormant season (Table 5). When the IM was applied in the dormant season, soil NO_3–N was not significantly different between depths in the control and 34 Mg ha^{-1} rates. However, subsoil NO_3–N at the 18 Mg ha^{-1} rate significantly increased compared to the surface soil (Table 5). Neither biosolids nor IM applied in the growing season influenced soil NO_3–N between soil depths in the treated plots.

A mulch rate × season of application × mulch type × position of soil sampling interaction influenced soil NO_3–N ($P < 0.0001$, Table 6). Soil NO_3–N was not significantly different between positions (10.2 mg kg^{-1}) in 18 Mg ha^{-1} biosolids rate, and significantly increased at underneath-biosolids positions (14.1 mg kg^{-1}) compared

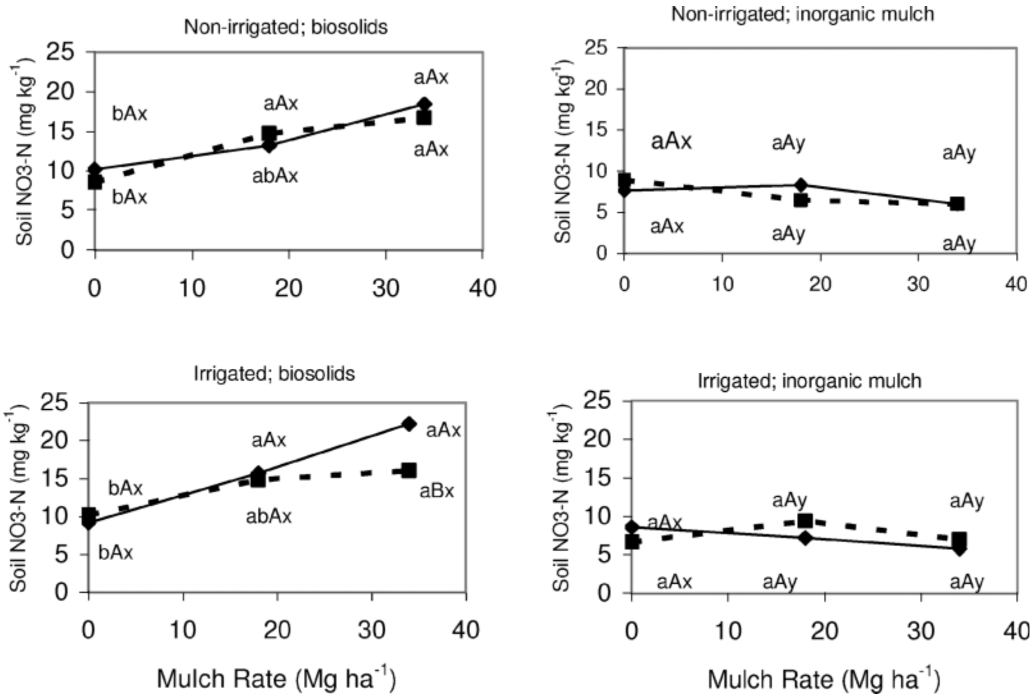

Fig. 3. Soil NO_3–N (mg kg^{-1}) in a Stellar soil as affected by biosolids rate, season of application, mulch, and irrigation (top figures: non-irrigated; bottom figures: irrigated) in August 1998. Biosolids were applied in 1998. Rate means within a season of application, mulch and irrigation level followed by the same lowercase letter (a, b, c) are not significantly different ($P > 0.05$). Season of application means within a rate, mulch, and irrigation followed by the same capital letter (A, B) are not significantly different ($P > 0.05$). Mulch means within a rate, season of application, and irrigation followed by the same lowercase letter (x, y) are not significantly different ($P > 0.05$). $n = 20$. Solid lines represent dormant season application; dashed lines represent growing season application. Data are back-transformed means from natural log-transformed data.

Table 5. Soil NO_3–N in a Stellar soil as affected by season of application, mulch, soil depth, rate, and irrigation in August 1998, Sierra Blanca, TX. Biosolids were applied in 1998. Data are back-transformed means from natural log-transformed data.

		Season of application			
		Dormant		Growing	
Rate	Soil depth	Biosolids	IM†	Biosolids	IM
Mg ha^{-1}	cm	mg kg^{-1}			
		Non-irrigated			
0	0–5	5.9a‡	6.1a	4.8b	5.0a
	5–15	6.1a	7.3a	7.8a	6.5a
18	0–5	11.3a	7.1a	7.8b	6.2a
	5–15	9.3a	8.6a	12.9a	6.6a
34	0–5	13.4a	6.5a	11.1a	5.7a
	5–15	10.5a	4.1b	8.9a	5.7a
		Irrigated			
0	0–5	6.1b	5.8a	6.4b	5.0b
	5–15	9.7a	6.7a	10.0a	9.4a
18	0–5	13.2a	6.1b	8.9a	8.1a
	5–15	8.3b	8.2a	11.3a	9.8a
34	0–5	16.9a	5.8a	10.8a	7.1a
	5–15	8.7b	5.4a	8.9a	6.7a

† Inert mulch.

‡ Soil depth means within a rate, mulch, season of application, and irrigation followed by the same letter are not significantly different ($P > 0.05$); $n = 20$.

to the interspaces between biosolids (10.2 mg kg^{-1}) at the 34 Mg ha^{-1} rate when biosolids were applied in the dormant season. When IM was applied, soil NO_3–N varied slightly across seasons and positions of sampling. Soil NO_3–N was not significantly between both positions when biosolids were applied in the growing seasons in all rates.

DISCUSSION

The presence of higher-order interactions detected in this study illustrate the complexity of factors influencing NO_3–N in this ecosystem and necessitated interpretation of simple main effects and simple effects; the most important experimental effects in this research involved comparisons between biosolids and inert mulch, and interactions between this factor, season of application, and depth of sampling.

Table 6. Soil NO_3–N in a Stellar soil as affected by season of application, mulch, position of sampling (underneath surface mulch, or in the interspaces between surface mulch particles), and rate of application in August 1998, Sierra Blanca, TX. Biosolids were applied in 1998. Data are back-transformed means from natural log-transformed data.

		Season of application			
		Dormant		Growing	
Rate	Position	Biosolids	IM†	Biosolids	IM
Mg ha^{-1}		mg kg^{-1}			
18	interspace	10.3a‡	7.2a	10.0a	8.5a
	underneath	10.5a	7.7a	10.1a	6.7b
34	interspace	10.2b	6.0a	9.8a	6.4a
	underneath	14.1a	4.9b	10.1a	6.2a

† Inert mulch.

‡ Position means within a rate, mulch, and season of application followed by the same letter are not significantly different ($P > 0.05$); $n = 40$.

Higher soil NO_3–N with surface application of biosolids in this study may be attributed to an increase in N mineralization and nitrification, as observed with biosolids application in incubation and field studies (Parker and Sommers, 1983; Barbarick et al., 1996; Pascual et al., 1998; Barajas-Aceves and Dendooven, 2001). Increases in soil NO_3–N at the end of the first growing season following biosolids application have also been observed by Aguilar et al. (1994) in a semiarid rangeland in New Mexico, Wester et al. (1995) in Chihuahuan Desert grasslands, and Mata-González et al. (2002) in greenhouse studies with desert soils. The addition of organic materials with a C to N ratio lower than 20:1 results in net soil N mineralization (Barbour et al., 1987; Tisdale et al., 1993). Biosolids applied in this study during 1998, with C to N ratios of 4.0 and 5.6 for dormant and growing season application, respectively, are therefore expected to increase soil NO_3–N. It is also likely that some of the nitrogen appearing as nitrate nitrogen in our measurements was directly added as ammonium and nitrified (rather than mineralized from organic nitrogen) when conditions for microbial activity were appropriate for this transformation. In control plots, lower soil NO_3–N concentration may be attributed to low availability of a substrate (organic matter) for N mineralization. Low substrate availability is the primary cause of low decomposition rates in Chihuahuan Desert soils (MacKay et al., 1987) and is the primary factor that inhibits nitrification in the soil (Tisdale et al., 1993).

Higher soil NO_3–N availability when biosolids were applied during the dormant season compared to the growing season in this study partially explains results observed in previous studies (e.g., Benton and Wester, 1998; Jurado and Wester, 2001; Mata-González et al., 2002) where enhanced forage production was observed following dormant season applications of biosolids compared to growing season applications. Increased soil NO_3–N, both earlier and throughout the plant growing season, with dormant application of biosolids, especially during the first year (1997), may be partially attributed to the presence of above-normal rainfall from March to June (wet spring season), promoting greater biosolids mineralization rates. However, the 18 Mg ha^{-1} biosolids rate resulted in the highest soil NO_3–N earlier in the plant growing season, suggesting that low biosolids rates produce better results under low rainfall conditions. A possible explanation relies on the observation that biosolids at higher rates of application can intercept small amounts of rainfall (Yan et al., 2000), and our results occurred during extremely dry months during 1998.

Mineralization and nitrification rates increase as biosolids organic N content increases (Barbarika et al., 1985; Hattori and Mukai, 1986) and biosolids C to N ratio decreases (Barbarika et al., 1985; Lerch et al., 1992; Gilmour and Skinner, 1999). Laboratory and field studies have shown that N mineralization was 27 and 37% of the organic nitrogen for the growing season and the first year (Gilmour et al., 2003). Also, surface application of biosolids in semiarid rangelands showed that total N in biosolids decreased from 50 to 10 g N kg^{-1} after 82 mo of exposure (Jaynes et al., 2003). Because biosolids composition varies seasonally (Sommers, 1977; USEPA, 1989) some of the variation in soil NO_3–N availability could be attributed to biosolids organic carbon and nitrogen contents. In this study, biosolids TKN was slightly higher under dormant applications (4.01 and 4.5%) than under growing season applications (2.3 and 3.5%, respectively, for 1997 and 1998), and C to N ratios were also slightly lower in dormant season applied–biosolids. Higher soil NO_3–N under dormant biosolids application may be partially attributed to these differences. However, it may also be attributed to the earlier onset of mineralization and nitrification rates as shown by higher soil NO_3–N in June 1997 and June 1998 during the first year after dormant applications of biosolids in this study. Smith et al. (1998) showed that soil NO_3–N formation was also controlled by time since soil incorporation in an incubation study.

A lag time of mineralization and nitrification rates is expected after application of biosolids (Hsieh et al., 1981; Beltrán-Hernández et al., 1999). Also, high N losses through volatilization under hot environmental conditions (Beauchamp et al., 1978; Harmel et al., 1997) may explain the reduced soil NO_3–N under surface application of biosolids in the growing season in this study. Benton and Wester (1998) observed more beneficial effects on plant growth after a dormant-season biosolids application (followed by a wet spring and summer) than after a growing-season biosolids application, even though biosolids TKN was higher in growing season application. The fact that irrigation provided after the growing season application of biosolids did not influence soil NO_3–N on most sampling dates suggests that additional water as we applied it (four applications of 15 mm, for a total of 60 mm) does not affect N mineralization and nitrification. Hsieh et al. (1981) also observed similar effects on mineralization after biosolids application to a sandy loam soil under both 0.06 and 0.33 bars soil-water potentials in an incubation study. In several settings, then, we observed either little or no response of soil NO_3–N to applied biosolids and/or irrigation. Soil microbial populations may have been small and likely were carbon-limited, so that higher rates of soil NO_3–N production were not achieved by added organic N or water. Additionally, the limiting step may be lower nitrification rates (because of relatively dry soils) rather than low mineralization rates.

The seasonal effect of biosolids application at the surface of desert grassland soils diminished after a year following application. However, this effect persisted one year after biosolids application in the subsurface soil as observed in this study. This may be attributed to more incorporation of dormant-applied biosolids into the soil profile compared to growing-applied biosolids because of longer residence time.

Slight increases in soil NO_3–N in 1997 but no response in 1998 with IM application may be attributed to the fact that IM did not provide a substrate for N mineralization. These results agree with research by MacKay et al. (1987) who indicated that soil microbial activity in Chihuahuan Desert soils is more limited by organic matter than by water availability.

An interesting pattern of soil NO_3–N vertical distribution was observed in our study. Under natural conditions (control plots), soil NO_3–N was slightly higher in the subsurface soil during both years. An opposite effect was observed under biosolids application, where soil NO_3–N throughout 1997 was generally higher in the surface soil than in subsurface soil regardless of season of application. When these plots were resampled in 1998 (the second year after one-time biosolids application in 1997), there continued to be a strong biosolids rate effect. However, there were much higher levels of soil NO_3–N in the subsurface soil compared to the surface soil in 1998 than in 1997. That is, soil NO_3–N increased in the subsurface soil over time. A gradual incorporation of biosolids into the soil could have taken place over time with subsurface soil NO_3–N being enhanced after 16 and/or 12 mo of soil–biosolids contact. The increase in soil NO_3–N may also be the result of leaching of NH_4–N and/or N mineralization from biosolids. It is important to emphasize that these soil samples were collected between plants from bare soil. Soil NO_3–N distribution may have been different if soil samples had been collected under the canopy of grass plants. Similar patterns of soil NO_3–N distribution were observed by Aguilar et al. (1994) in a semiarid rangeland after spring application of biosolids at 45 Mg ha^{-1}.

In general, soil NO_3–N was not influenced by position of sampling: both interspace and underneath-biosolids sampling locations had similar soil NO_3–N concentrations on all dates in 1997- and 1998-treated plots. Thus, soil NO_3–N was relatively uniformly distributed along a horizontal gradient at the depths we sampled.

Soil NO_3–N levels depended on biosolids rate and season of application. Dormant-season application of biosolids increased soil NO_3–N levels (this study) and promoted grass growth (e.g., Benton and Wester, 1998; Jurado and Wester, 2001) more than a growing season application of biosolids under a wet spring and low summer rainfall. In contrast, season of application did not affect soil NO_3–N levels during a year with a dry spring season and close to normal summer rainfall.

CONCLUSIONS

Surface application of biosolids has the potential to improve the fertility of desert soils (interplant spaces) by increasing plant available nitrogen. Soil NO_3–N was increased at an earlier date under dormant season–applied biosolids compared to growing season application regardless of precipitation. The inert mulch did not have significant effects on soil NO_3–N throughout the spring and summer seasons. Therefore, we attribute the increased levels of soil NO_3–N under biosolids primarily to chemical effects of biosolids rather than to indirect effects that biosolids may have had on microenvironmental conditions (e.g., by affecting soil temperature or soil water). Soil NO_3–N increased more with dormant season application of biosolids compared to growing season application throughout the summer under normal to above normal rainfall conditions. In dry conditions, the seasonal effect of biosolids was not observed in soil NO_3–N throughout the summer. Irrigation did not have significant effects on soil NO_3–N. Soil NO_3–N levels were relatively constant across horizontal sampling distances (i.e., underneath or between surface mulch positions) but increased vertically over time, with carryover effects at least 15 mo after application. Soil NO_3–N remained higher in the surface soil during the first year and increased in the subsurface during the second year under surface-applied biosolids. Our results show that differential response of grass growth to season of biosolids application is related to soil NO_3–N release patterns and biosolids residence time in this environment.

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