



Shoot and root biomass of desert grasses as affected by biosolids application

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This research evaluated the effects of level and season of biosolids application and irrigation regime on shoot and root biomass production of blue grama (*Bouteloua gracilis* (H.B.K.) Lag. ex Steud.) and tobosagrass (*Hilaria mutica* (Buckl.) Benth.), two perennial, warm season grasses of Chihuahuan Desert rangelands. Plants of both species were transplanted to pots and maintained under a rain-out shelter. The plants were treated either in the spring or summer with biosolids at levels of 0, 7, 18, 34, and 90 dry Mg ha⁻¹ and irrigated at 40% or 80% field capacity soil water content. In general, biosolids increased shoot biomass of both species, which was partly a result of the increased soil NO₃-N concentrations that followed biosolids application. More biomass was allocated to the roots of the grasses when biosolids and irrigation levels were low. In contrast, more biomass was allocated to the shoots when biosolids and irrigation levels were high. Shoot biomass production and soil NO₃-N concentrations were enhanced more by the spring application of biosolids than by the summer application. The season of application influences the beneficial effect of biosolids on desert grasses.

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Keywords: biosolids; *Bouteloua gracilis*; *Hilaria mutica*; root:shoot ratio; season of biosolids application

Introduction

Biosolids, historically known as sewage sludge, are nutrient-rich solids that result as a by-product of municipal wastewater treatment and meet the criteria for land application in the United States (U.S. Environmental Protection Agency, 1999). Land application of biosolids is considered beneficial because it allows the utilization of mineral and organic constituents of biosolids for soil and plants (Epstein & Alpert, 1981; U.S. Environmental Protection Agency, 1989). According to Sommers (1977), anaerobically produced biosolids from a variety of sources had a mean organic-C content of 27.6% and a mean total-N concentration of 5%. Relatively few studies have been conducted to document the effects of land application of biosolids on semi-arid rangelands (Fresquez *et al.*, 1990; Benton & Wester, 1998; Pierce *et al.*, 1998; Jurado & Wester, 2001). Application of biosolids to semi-arid rangelands represents a sound manner of recycling biosolids because it helps to enhance soil nutrient levels in these

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environments (Fresquez *et al.*, 1990). Semi-arid rangelands offer ideal opportunities for biosolids recycling because (1) they occur throughout much of the world and (2) they typically have limited soil water, deep water tables, neutral to basic soils, and high soil cation exchange capacity (Holecheck *et al.*, 1989; White *et al.*, 1997); conditions that represent little risk for soil and water contamination from biosolids (U.S. Environmental Protection Agency, 1989).

Fresquez *et al.* (1990) reported an increase in vegetative production and forage quality of blue grama (*Bouteloua gracilis* (H.B.K.) Lag. ex Steud.) as a result of boosting soil nutrients by applying biosolids at levels of 45 and 90 dry Mg ha⁻¹ in a semi-arid rangeland. Benton & Wester (1998) reported an increase in tobosagrass (*Hilaria mutica* (Buckl.) Benth.) yield following applications of biosolids at levels of 7, 18, and 34 dry Mg ha⁻¹ in the Chihuahuan Desert. Although dormant season applications of biosolids seem to be more beneficial for plant growth than growing season applications during the year of biosolids application (Benton & Wester, 1998), explanations for this phenomenon have not been documented.

Fundamental knowledge is limited on how biosolids beneficially affect semi-arid grasses. Application of biosolids to semi-arid rangelands has the potential of altering the nutrient status of the rhizosphere (Fresquez *et al.*, 1990), which likely affects not only the above-ground vegetative growth of range plants, but also the carbohydrate allocation to roots and shoots (Chapin, 1980). Previous studies have shown that low nutrient availability promotes the allocation of reserves to root tissues at the expense of shoot growth (McIntyre, 1964; Christie & Moorby, 1975). Water supply can also modify the nutrient availability of soils (Chapin, 1991) and the carbohydrate allocation in plants (Spollen *et al.*, 1993).

We hypothesized that low levels of biosolids application and low irrigation levels can promote preferential production of root biomass at the expense of the shoot growth of blue grama and tobosagrass. We also tested the hypothesis that the favorable shoot growth effect of spring application over summer application of biosolids is related to changes in soil nutrient status. The objectives of this research were (1) to evaluate as to how levels and seasons of application of biosolids, as well as different irrigation levels affect shoot biomass and root:shoot ratio (RSR) of blue grama and tobosagrass, and (2) to determine if the effect of biosolids application on shoot biomass is related to changes in the soil NO₃-N concentration.

Materials and methods

The study area is located on the Sierra Blanca Ranch, about 140 km south-east of El Paso, Texas in the Chihuahuan Desert. The area has an annual average precipitation of 310 mm, 65% of which occurs from July through September dictating the growing season period for perennial, warm season grasses. The experiments were conducted in 1997 and 1998 under a semi-cylindrical rain-out shelter (26 m × 4.5 m) covered with greenhouse plastic film.

Two soil types from the Sierra Blanca Ranch were used: (1) an Armesa taxadjunct fine sandy loam, which is a fine, loamy, mixed, thermic, Ustic Haplocalcid (B.L. Allen and C. Moffet, pers. comm.), and (2) a Stellar taxadjunct loam, which is a fine mixed, superactive, thermic Vertic Paleargid with the surface horizon overlying an argillic and a calcic horizon (Casby-Horton, 1997). Since the Natural Resources Conservation Service has not officially correlated the soils of Hudspeth County, the names of the soil series used in this study are taxadjuncts or variants that may change in the future. The predominant plant species growing on the Armesa soil are black grama (*Bouteloua eriopoda* (Torr.) Torr.), blue grama, ear muhly (*Muhlenbergia arenacea* (Buckl.) A.S. Hitchc.), burrograss (*Scleropogon brevifolius* Phil.), soaptree yucca (*Yucca elata*

Table 1. Chemical composition of the biosolids applied

Variable	Spring 1997	Summer 1997	Spring 1998	Summer 1998
TKN (%)*	4.48	2.36	4.94	3.78
OM (%)†	nm‡	nm	36.45	46.28
P (%)	2.02	1.98	2.43	2.03
K (%)	0.11	0.13	0.12	0.13
Ca (%)	2.44	2.23	2.15	2.66
Mg (%)	0.67	0.56	0.74	0.68
S (%)	1.21	1.33	1.3	1.34
Na (%)	0.08	0.09	0.02	0.10
Z (g kg ⁻¹)	1.02	1.09	0.89	1.19
NH ₄ -N (mg kg ⁻¹)	nm	nm	6.67	4.24
Fe (mg kg ⁻¹)	14.55	30.14	36.86	9.70
Mn (mg kg ⁻¹)	0.97	0.52	2.25	0.82
Cu (mg kg ⁻¹)	1.07	0.96	0.81	0.95
Al (mg kg ⁻¹)	9.49	10.03	7.58	9.06
NO ₃ -N (mg kg ⁻¹)	nm	nm	68.6	28.33
Ni (mg kg ⁻¹)	35.00	50.00	21.13	25.91
Cd (mg kg ⁻¹)	6.00	nd§	2.87	nd
Pb (mg kg ⁻¹)	215.00	233.92	210.70	260.20
B (mg kg ⁻¹)	24.00	22.20	8.60	6.60
EC (dS m ⁻¹)¶	5.64	6.66	8.13	12.24

*Total Kjeldahl nitrogen.

†Organic matter.

‡Not measured.

§Not detected.

¶Electrical conductivity.

Engelm.), and Mormon tea (*Ephedra trifurca* Torr.). The predominant plants growing on the Stellar soil are tobosagrass, alkali sacaton (*Sporobolus airoides* (Torr.) Torr.), and mesquite (*Prosopis glandulosa* (Torr.) var. *glandulosa*).

One hundred and sixty pots (total volume 14.7 l; 300 mm deep; and 250 mm diameter) were used in the experiments; half of them were filled with Armesa soil and the other half with Stellar soil. Blue grama and tobosagrass plants with four or five tillers were collected in 1997 and 1998 from the same areas where the Armesa and the Stellar soils were obtained in the field and transplanted to pots with Armesa and Stellar soil, respectively. Transplanting was done in February and immediately after transplanting, the plants were irrigated regularly to ensure establishment.

Half of the plants of each species were treated with biosolids during March (spring application) and the other half were treated during June (summer application) of each year. Although the plants were well watered during the establishment period, irrigation was withheld a few days before the spring application in order to ensure that higher soil moisture did not favor the spring over the summer application. In both seasons of application, biosolids were surface-applied at levels of 0, 7, 18, 34, and 90 dry Mg ha⁻¹. The highest level of application was selected for research purposes to establish an upper limit to the response of biosolids, since it is considered as an excessive level for commercial application. The biosolids that were used in this study were provided by a private corporation that contracted with New York City for land-applying a portion of their biosolids from residential wastewater treatment plants. The biosolids used were class B and did not contain industrial residues; their chemical composition is shown in Table 1.

Plants were subjected to two irrigation levels: 40% and 80% of field capacity; i.e. the amount of water that each soil holds at field capacity was multiplied by 0.40 and 0.80 to obtain the amount of water applied for each treatment. The field capacity of each soil was determined by using a pressure plate (Richards, 1965). The Stellar soil's field capacity was 28.4% and the Armesa's was 19.4% water on a volumetric (v/v) basis. A field study showed that soil volumetric (v/v) water content (0 to 15 cm depth) can vary from 13% to 33% in the Stellar soil and from 12% to 19% in the Armesa soil according to the season of the year (Jurado, 2000). After the spring application of biosolids, every pot, irrespective of season of biosolids application, was irrigated once a week until the end of the experiments with the necessary amount of water to bring the soil water content to either 40% or 80% field capacity.

The experimental unit was a pot containing one plant of either blue grama or tobosagrass. A factorial experiment ($5 \times 2 \times 2$) was established by combining five levels of biosolids application, two seasons of biosolids application, and two levels of irrigation. As a result, 20 treatments were applied to each species and each experimental unit was replicated 4 times. A randomized block design with four blocks was used. Within each block, the 20 treatments were physically arranged completely at random. The experiments that are reported in this paper were part of a larger study that also measured photosynthesis rates of plants (Mata-González, 1999). The blocks corresponded to different days in which photosynthesis measurements were conducted because it was impossible to measure all the plants on the same day. Data normality were tested by the Shapiro–Wilk's test prior to performing analyses of variance and regression analyses.

In order to assess sphericity, the Greenhouse–Geisser estimator of θ was calculated and used to modify the F test, assuming that sphericity was violated. It was found that, even assuming that sphericity was violated, a great majority of the significant effects found with the normal F tests, were also found with the Greenhouse–Geisser modified F tests. Since violation of sphericity did not change the output of these analyses of variance in a critical manner, the normal F tests were used to test the hypotheses of interest. Treatment mean separation was obtained with the Fisher's protected least significant difference (LSD) test and significant differences were declared at $p < 0.05$. Mean separation was obtained with the general error term.

At the end of the experiments, in late August, the shoots of all plants were harvested and the roots were obtained by carefully washing soil from the root systems with tap water over a 5 mm mesh screen. Upon collection of shoot and root tissues, the shoots and roots were placed in a forced-air oven to dry for 24 h at 75°C. Soil samples were taken at the end of the experiments from every pot and air-dried. The $\text{NO}_3\text{-N}$ concentration from each soil sample was determined spectrophotometrically by Cd reduction (Mulvaney, 1996). All measurements obtained in this study were made only after one growing season, consequently no measurements represent any 'carryover' effects.

Results

In both years of this study, shoot biomass of blue grama and tobosagrass increased as a result of increasing the levels of biosolids and irrigation, but the effects of these factors were not interactive (Mata-González, 1999). The increase in irrigation level from 40% to 80% field capacity produced increases of more than 100% in shoot biomass in both species (Mata-González, 1999). Shoot biomass of blue grama was affected by the interaction of level and season of biosolids application in 1998 (Fig. 1). A significant quadratic regression explained 95% of shoot biomass variation due to biosolids level in the spring application. Plants treated in the spring had about 100% and 200% higher

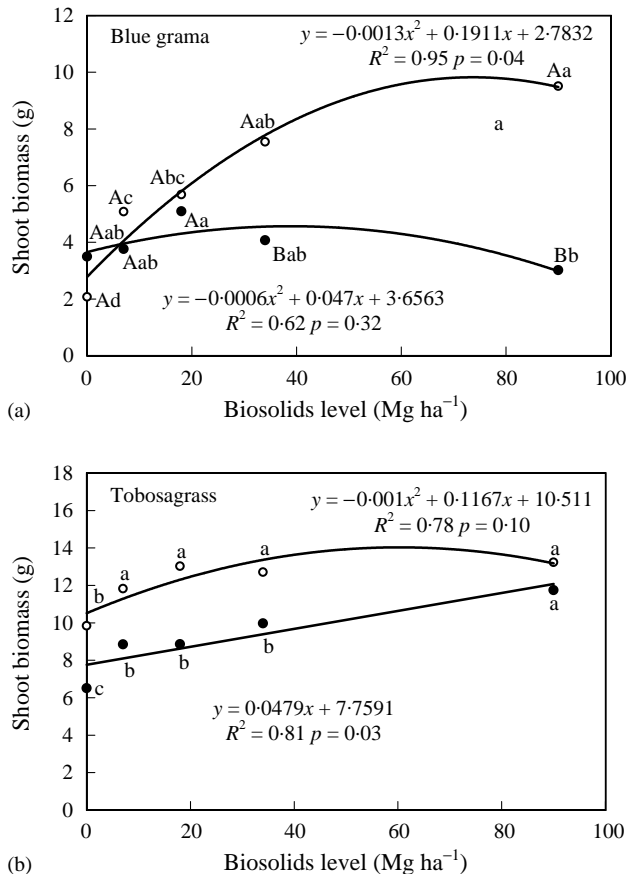


Figure 1. (a) Shoot biomass (g) of blue grama in 1998 as affected by the level and season of biosolids application (different capital letters within a biosolids level indicate significant difference between seasons at $p < 0.05$; different lowercase letters within a season indicate significant difference between levels at $p < 0.05$): (○) spring application; (●) summer application. (b) Shoot biomass (g) of tobosagrass in 1997 and 1998 as affected by biosolids level (different lowercase letters indicate significant difference at $p < 0.05$): (○) 1997; (●) 1998.

shoot biomass than plants treated in the summer at levels of 34 and 90 Mg ha^{-1} of biosolids, respectively. In contrast, when the application levels were 18 Mg ha^{-1} , or less, the season of biosolids application did not produce significant differences (Fig. 1). The positive effect of increasing biosolids levels on shoot biomass of blue grama was mostly restricted to the spring application.

In 1997 and 1998, tobosagrass exhibited an increase in shoot biomass as a result of biosolids application (Fig. 1). In both years, the plants that received no biosolids produced lower shoot biomass than plants treated with 7, 18, 34, or 90 Mg ha^{-1} (Fig. 1). The season of biosolids application also affected the shoot biomass of tobosagrass (Fig. 2). In 1997, the spring application of biosolids resulted in 12% higher shoot biomass than the summer application, whereas in 1998, the spring application produced 26% more shoot biomass than the summer application (Fig. 2).

Soil $\text{NO}_3\text{-N}$ increased as biosolids levels increased in both soils and this effect was similar in both years of the study (Mata-González, 1999). In 1998, $\text{NO}_3\text{-N}$ concentration in the Armesa soil was affected by the interaction of season and the

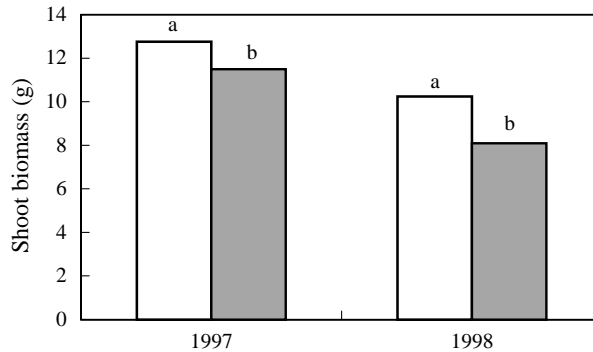


Figure 2. Shoot biomass (g) of tobosagrass in 1997 and 1998 as affected by the season of biosolids application (different lowercase letters indicate significant difference at $p < 0.05$): (□) spring application; (■) summer application.

Table 2. Soil $\text{NO}_3\text{-N}$ (mg kg^{-1}) in the Armesa soil as affected by the level and season of biosolids application in 1998

Biosolids level (Mg ha^{-1})	Season of biosolids application	
	Spring	Summer
0	10.31 Acd*	10.91 Ab
7	8.40 Ad*	12.47 Ab
18	16.24 Ac	12.83 Ab
34	42.83 Ab	14.73 Bb
90	78.11 Aa	44.23 Ba

*Different capital letters within a level indicate significant differences between seasons at $p < 0.05$; different lowercase letters within a season indicate significant differences between levels at $p < 0.05$.

level of biosolids application (Table 2). When biosolids were applied at 0, 7, and 18 Mg ha^{-1} , spring and summer applications did not produce differences in soil $\text{NO}_3\text{-N}$ concentration. However, the spring application produced about 200% and 80% higher soil $\text{NO}_3\text{-N}$ concentrations than the summer application when biosolids were applied at levels of 34 and 90 Mg ha^{-1} , respectively. In pots treated in the spring, a general increase in soil $\text{NO}_3\text{-N}$ concentrations was observed as biosolids levels increased (Table 2). In contrast, with the exception of pots treated with 90 Mg ha^{-1} of biosolids, pots treated in the summer showed little change as a result of increasing biosolids application levels (Table 2). The concentration of $\text{NO}_3\text{-N}$ in the Stellar soil was also higher when biosolids were applied in the spring than in the summer (Mata-González, 1999). In blue grama and tobosagrass, 80% and 96% of the variation in shoot biomass due to soil $\text{NO}_3\text{-N}$ concentration was accounted for by significant linear and quadratic regressions, respectively (Fig. 3).

Application of biosolids reduced RSRs in blue grama. In 1998, blue grama plants receiving no biosolids had 81% higher RSRs than plants receiving 90 Mg ha^{-1} of biosolids (Fig. 4). Likewise, tobosagrass in 1997 had higher RSRs when plants had no biosolids than when plants were treated with biosolids from 7 to 90 Mg ha^{-1} (Fig. 4). In 1997, blue grama RSRs were significantly affected by the interaction of the season of biosolids application and irrigation level (Fig. 5). In both the spring and summer applications, the low irrigation level resulted in significantly higher RSRs than the high irrigation level. In the spring application, irrigation at 40% field capacity produced

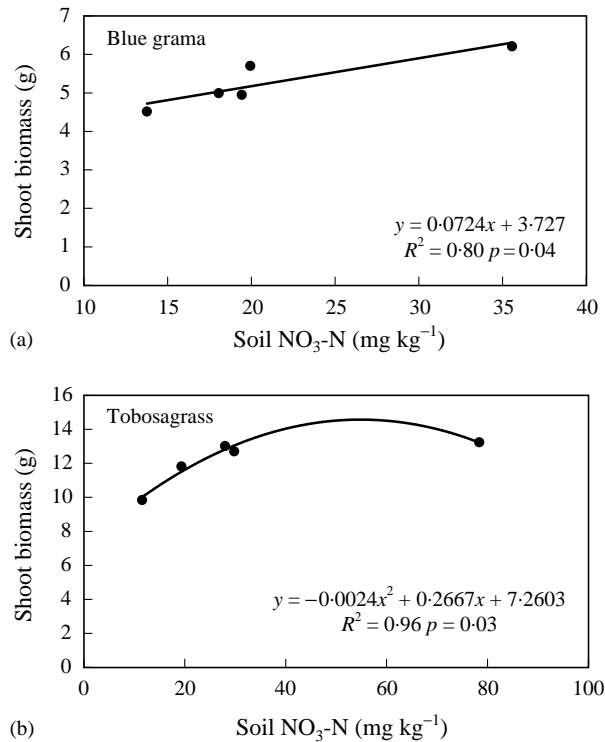


Figure 3. Shoot biomass (g) as affected by soil NO₃-N concentration in (a) blue grama and (b) tobosagrass in 1997.

RSRs two-fold greater than irrigation at 80% field capacity. In the summer application, irrigation at 40% field capacity produced RSRs three-fold greater than irrigation at 80% field capacity. Summer application of biosolids produced higher RSRs than spring application when blue grama plants were irrigated at 40% field capacity. On the other hand, when plants were irrigated at 80% field capacity, there was no difference between seasons of biosolids application (Fig. 5).

In 1997, tobosagrass RSRs were affected by the interaction of the season of biosolids application and irrigation level (Fig. 5). In the summer application, irrigation at 40% field capacity resulted in higher RSRs than irrigation at 80% field capacity. In the spring application, tobosagrass RSRs were not affected by irrigation levels. Summer application of biosolids produced a higher RSR than spring application when blue grama plants were irrigated at 40% field capacity. However, when plants were irrigated at 80% field capacity, there was no difference between seasons of biosolids application (Fig. 5).

Discussion

The observation that quadratic equations might describe the response of shoot biomass to increasing biosolids levels is consistent with a previous report (Benton & Wester, 1998). The increase in shoot biomass in blue grama and tobosagrass produced by the application of biosolids is in agreement with previous field studies in semi-arid grasses (Fresquez *et al.*, 1990; Benton & Wester, 1998; Jurado & Wester, 2001). These

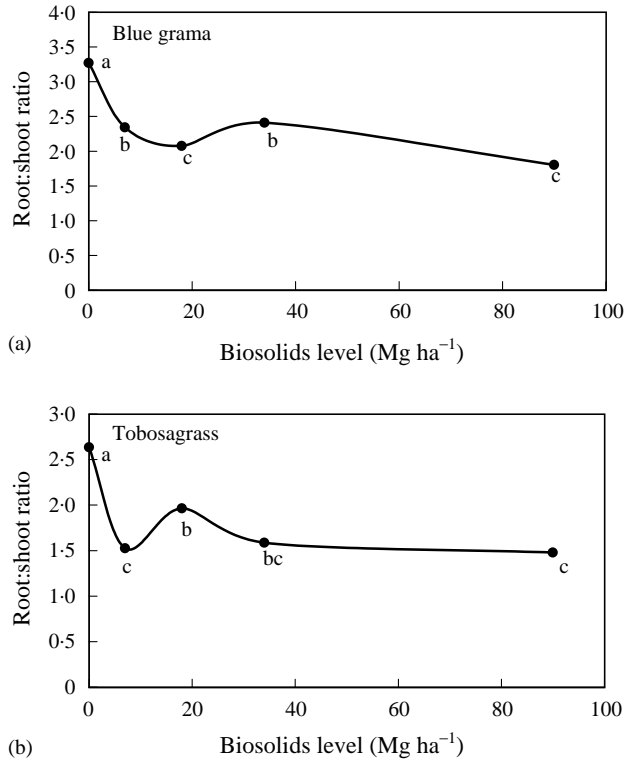


Figure 4. Root:shoot ratio of (a) blue grama in 1998 and (b) tobosagrass in 1997 as affected by the level of biosolids application (different lowercase letters indicate significant difference at $p < 0.05$).

studies attributed the increase in biomass, at least to some extent, to the soil nutrients provided by biosolids. The increase in shoot biomass of blue grama that Fresquez *et al.* (1990) reported corresponded to an increase of soil-N concentration following biosolids application.

In this study, the increase in biosolids level produced increases in soil $\text{NO}_3\text{-N}$ concentration, which were related to the variation in shoot biomass of blue grama and tobosagrass. The concentration of soil $\text{NO}_3\text{-N}$ was determined at the end of the experiments, immediately after harvesting the plants. Therefore, soil $\text{NO}_3\text{-N}$, as obtained in this study is an indicator of residual soil $\text{NO}_3\text{-N}$ after plant utilization (Sullivan *et al.*, 1997). The variation in shoot biomass cannot be directly attributed to residual soil $\text{NO}_3\text{-N}$ concentrations. However, the increase in shoot biomass and residual soil $\text{NO}_3\text{-N}$ concentrations as biosolids levels increased indicates that biosolids were able to supply $\text{NO}_3\text{-N}$ for plant growth and still provide residual mineral N available for plant uptake for the following growing season. This is consistent with the results of White *et al.* (1997) who found that biosolids can provide soil $\text{NO}_3\text{-N}$ several years after a single application to a semi-arid rangeland. Soil $\text{NO}_3\text{-N}$ is a readily available form of N for plant uptake, and according to Schenk (1996), it is the dominant form of N available to plants except in very acidic or anaerobic soils. The determination of soil $\text{NO}_3\text{-N}$ after biosolids application provides an indicator of the contribution of biosolids to the pool of N available for plants (Stevenson, 1986).

Our results indicate that spring application of biosolids is more beneficial to shoot growth than summer application, which is consistent with findings by Benton & Wester (1998). This effect might be associated with the higher soil $\text{NO}_3\text{-N}$

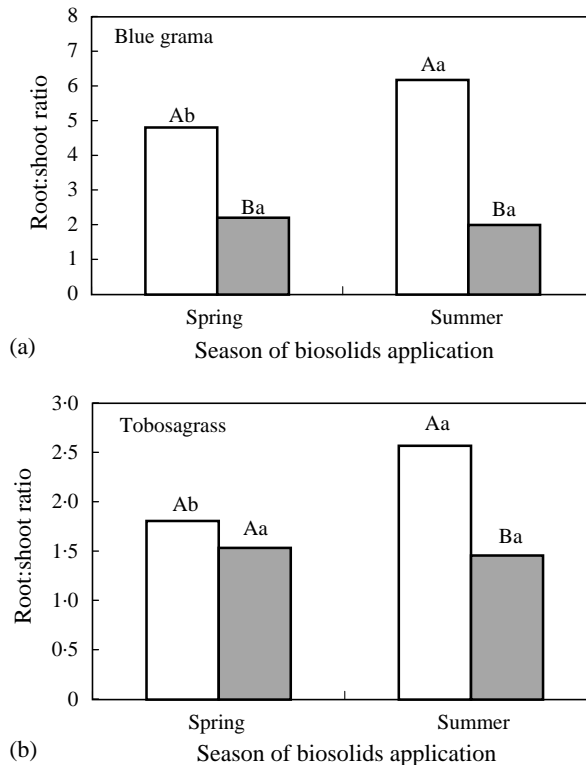


Figure 5. Root:shoot ratio of (a) blue grama and (b) tobosagrass as affected by the season of biosolids application and irrigation level in 1997 (different capital letters within a season indicate significant difference between irrigation levels at $p < 0.05$; different lowercase letters within an irrigation level indicate significant difference between seasons at $p < 0.05$): (□) 40% field capacity; (■) 80% field capacity.

concentration that also resulted from the spring application. Concentrations of $\text{NO}_3\text{-N}$ in the Armesa soil were significantly higher when soils were treated in the spring than in the summer with 34 and 90 Mg ha^{-1} of biosolids. Under the same biosolids levels, shoot biomass of blue grama was higher in plants treated in the spring than in the summer. Our results support Jurado (2000), who reported that soil $\text{NO}_3\text{-N}$ concentration was higher in plots treated with biosolids in the spring than in the summer on two different soil types and under relatively dry conditions in 2 years.

Soils treated with biosolids in the spring and summer had additional organic matter 4 months and 1 month, respectively, before the onset of the growing season (July). Therefore, one factor that may have favored a higher N availability under spring application was the residence time of biosolids. Availability of organic matter is important to activate the decomposition process in soils of the Chihuahuan Desert (MacKay *et al.*, 1987). It is likely that biosolids applied in the spring provided a substrate and promoted the activation of soil decomposers earlier than biosolids applied in the summer (Jurado, 2000). This explanation is challenged, however, by the fact that biosolids applied in the spring of 1997 and 1998 were higher in total-N than biosolids applied in the summer of both years (Table 1). It is possible that the spring application of biosolids resulted in higher available soil-N and higher plant growth than the summer application because of the intrinsic chemical nature of the biosolids applied. However, in the study by Benton & Wester (1998), the concentration of total-N was about 20% higher in the biosolids applied in the

summer than in the biosolids applied in the spring and yet, the spring application of biosolids resulted in higher plant shoot biomass than the summer application. This argues against the possibility that the advantage of spring application observed in this study was only due to the intrinsic nature of the biosolids applied.

In general, RSR tended to decrease with the increase in biosolids and irrigation levels. A previous study in the Chihuahuan Desert reported a reduction of tobosagrass root biomass in plants treated with 7, 18, and 34 Mg ha⁻¹ of biosolids compared to plants without biosolids (Cooley, 1998). Cooley also reported a decrease of root biomass in irrigated plants compared to non-irrigated plants. Our results suggest that the higher soil-N availability obtained by increasing biosolids application levels was probably responsible for the decrease in RSR of blue grama and tobosagrass. It is well documented that under nitrogen limitations in the rooting medium, plants tend to allocate carbohydrates to the roots (McIntyre, 1964; Chapin, 1980; Levin *et al.*, 1989), thereby, increasing root mass and the root's 'foraging' capacity for soil-N (Marschner, 1995).

RSR provides an indication of the plant's ability to allocate resources to different plant parts in response to external conditions (Marschner, 1995). The most widely used model to explain RSR as affected by external factors is the Thornley (1998) model. This model suggests that plant growth depends on the presence of N and C; N is obtained by the roots and transported to the shoots, whereas C is obtained by the shoots and transported to the roots. When N or C are deficient, their transport to shoots or roots, respectively, is decreased by a drop in the substrate gradient. As a result, a decrease in the supply of N is reflected in low N transport to the shoot, which increases growth partitioning toward the root. Similarly, a decrease in the supply of C will result in a limited amount of C translocation to the root, promoting an increase in the growth of the shoot. Our results are consistent with Thornley's model.

In our study, high RSRs were also observed in plants under low levels of irrigation. Spollen *et al.* (1993) pointed out that plants growing at low water potentials develop a high concentration of ABA, which is required to maintain root elongation while inhibiting shoot growth. In addition, Spollen *et al.* (1993) reviewed the evidence suggesting that cell wall extensibility, which is an important factor determining cell growth, is less affected in root cells than in shoot cells under water shortages.

In this study, a clear pattern evolved in which the highest RSRs were obtained in plants irrigated at 40% field capacity and treated with biosolids in the summer. Summer application of biosolids in some cases resulted in lower soil NO₃-N than the spring application. Therefore, it seems that plants irrigated at 40% field capacity and treated in the summer with biosolids developed the highest RSR in response to the low water and low nitrogen levels in the rooting medium. Water-stressed plants as well as nutrient-stressed plants tend to increase their RSRs in a similar manner (Chapin, 1991). Furthermore, water deficits may have a direct effect on reducing nutrient availability, so it is not unusual that a nutrient stress follows a water stress (Chapin, 1991).

Plants may not need an extensive root system to acquire nutrients and water when these resources are sufficiently available in the soil. Therefore, under these conditions, resource use efficiency by roots increases. In agreement with this, Robinson (1986) reported that only 20% of the root mass is necessary to supply enough N to satisfy the demand of a plant. This is achieved when N is readily available in the soil, promoting a high N uptake rate by roots.

Conclusions

Our data support the hypothesis that low biosolids levels and low irrigation regimes tend to increase root biomass at the expense of shoot growth. Lower soil-N availability

as the level of biosolids decreased was probably responsible for the increase in RSR of blue grama and tobosagrass. Water and biosolids exerted similar effects on biomass allocation. In general, blue grama and tobosagrass, the two desert grasses of this study, were similarly affected by the application of biosolids. Biosolids application produced an increase in shoot biomass of both species and an increase in soil $\text{NO}_3\text{-N}$ concentration. Spring application of biosolids produced higher shoot growth than summer application. The longer exposure of biosolids to the decomposing agents from the spring application favored higher soil $\text{NO}_3\text{-N}$ concentrations, which supports our second hypothesis. We suggest that in order to achieve more beneficial plant responses in the first year of application, biosolids should be applied a few months before the onset of the growing season.

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References

- Benton, M.W. & Wester, D.B. (1998). Biosolids effects on tobosagrass and alkali sacaton in a Chihuahuan desert grassland. *Journal of Environmental Quality*, **27**: 199–208.
- Casby-Horton, S.M. (1997). Soil genesis and soil-geomorphic relationships in an area near Sierra Blanca, Texas. Ph.D. dissertation, Texas Tech University, Lubbock, TX. 165 pp.
- Chapin, F.S. III. (1980). The mineral nutrition of wild plants. *Annual Review of Ecology and Systematics*, **11**: 233–260.
- Chapin, F.S. III. (1991). Effects of multiple environmental stresses on nutrient availability and use. In: Mooney, H.A., Winner, W.E. & Pell, E.J. (Eds), *Response of Plants to Multiple Stresses*, pp. 67–88. San Diego, CA: Academic Press. 422 pp.
- Christie, E.K. & Moorby, J. (1975). Physiological responses of semiarid grasses. I. The influence of phosphorus supply on growth and phosphorus absorption. *Australian Journal of Agricultural Research*, **26**: 423–436.
- Cooley, P.E. (1998). Biosolids and chemical fertilizer application on the Chihuahuan Desert grasslands. M.Sc. thesis, Texas Tech University, Lubbock, TX. 182 pp.
- Epstein, E. & Alpert, J.E. (1981). Land application of sewage sludge with special emphasis on composting. In: Shuval, H. (Ed.), *Developments in Arid Zone Ecology and Environmental Quality*, pp. 191–209. Philadelphia, PA: Balaban ISS. 418 pp.
- Fresquez, P.R., Francis, R.E. & Dennis, G.L. (1990). Soil and vegetation responses to sewage sludge on a degraded semiarid broom snakeweed/blue grama plant community. *Journal of Range Management*, **43**: 325–331.
- Holecheck, J.L., Pieper, R.D. & Herbel, C.H. (1989). *Range Management, Principles and Practices*. Englewood Cliffs, NJ: Prentice-Hall. 501 pp.
- Jurado, P. (2000). Effects of biosolids and an inorganic mulch on soil-plant relationships in two Chihuahuan desert grasslands. Ph.D. dissertation, Texas Tech University, Lubbock, TX. 146 pp.
- Jurado, P. & Wester, D.B. (2001). Effects of biosolids on tobosagrass growth in the Chihuahuan desert. *Journal of Range Management*, **54**: 89–95.
- Levin, S.A., Mooney, H.A. & Field, C. (1989). The dependence of plant root:shoot ratios on internal nitrogen concentration. *Annals of Botany*, **64**: 71–75.
- MacKay, W.P., Fisher, F.M., Silva, S. & Whitford, W.G. (1987). The effects of nitrogen, water and sulfur amendments on surface litter decomposition in the Chihuahuan Desert. *Journal of Arid Environments*, **12**: 223–232.

- Marschner, H. (1995). *Mineral Nutrition of Higher Plants* (2nd Edn). London: Academic Press. 889 pp.
- Mata-González, R. (1999). Influence of biosolids application on growth, nitrogen uptake, and photosynthesis of two desert grasses. Ph.D. dissertation, Texas Tech University, Lubbock, TX. 131 pp.
- McIntyre, G.I. (1964). Influence of nitrogen nutrition on bud and rhizome development in *Agropyron repens*. *Nature*, **203**: 1084–1085.
- Mulvaney, R.L. (1996). Nitrogen-inorganic forms. In: Sparks, D.L., Page, A.L., Helmke, P.A., Loeppert, R.H., Soltanpour, P.N., Tabatabai, M.A., Johnson, C.T., & Sumner, M.E. (Eds), *Methods of Soil Analysis*. Part 3. *Chemical Methods*. Soil Science Society of America Book Series No. 5, pp. 1123–1151. Madison, WI: American Society of Agronomy-Soil Science Society of America. 1358 pp.
- Pierce, B.L., Redente, E.F., Barbarick, K.A., Brobst, R.B. & Hageman, P. (1998). Plant biomass and elemental changes in shrubland forages following biosolids application. *Journal of Environmental Quality*, **27**: 789–794.
- Richards, L.A. (1965). Physical condition of water in soil. In: Black, C.A. (Ed.), *Methods of Soil Analysis*. Part I. *Agronomy Series*, pp. 128–152. Madison, WI: American Society of Agronomy. 1572 pp.
- Robinson, D. (1986). Compensatory changes in the partitioning of dry matter in relation to the nitrogen uptake and optimal variations in growth. *Annals of Botany*, **58**: 841–848.
- Schenk, M.K. (1996). Regulation of nitrogen uptake on the whole plant level. *Plant and Soil*, **181**: 131–137.
- Sommers, L.E. (1977). Chemical composition of sewage sludges and analysis of their potential use as fertilizers. *Journal of Environmental Quality*, **6**: 225–232.
- Spollen, W.G., Sharp, R.E., Saab, I.N. & Wu, Y. (1993). Regulation of cell expansion in roots and shoots at low water potentials. In: Smith, J.A.C. & Griffiths, H. (Eds), *Water Deficits, Plant Responses from Cells to Community*, pp. 37–52. Oxford, U.K.: BIOS Scientific Publishers. 345 pp.
- Stevenson, F.J. (1986). *Cycles of Soil*. New York: John Wiley and Sons. 380 pp.
- Sullivan, D.M., Fransen, S.C., Cogger, C.G. & Bary, A.I. (1997). Biosolids and dairy manure as nitrogen sources for prairiegrass on poorly grained soils. *Journal of Production Agriculture*, **10**: 589–596.
- Thornley, J.H.M. (1998). Modelling shoot:root relations: the only way forward? *Annals of Botany*, **81**: 165–171.
- U.S. Environmental Protection Agency. (1989). *Environmental Regulations and Technology. Use and Disposal of Municipal Wastewater Sludge*. EPA 625/10-84-003.
- U.S. Environmental Protection Agency. (1999). *Biosolids Generation, Use, and Disposal in The United States*. EPA530-R99-009.
- White, C.S., Loftin, S.R. & Aguilar, R. (1997). Application of biosolids to a degraded semiarid rangeland: nine-year response. *Journal of Environmental Quality*, **26**: 1663–1671.