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Effects of biosolids on tobosagrass growth in the Chihuahuan desert

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Abstract

Little information is available about seasonal application and carry-over effects of biosolids application to semi-arid grasslands. Biosolids rates of 0 (control), 7, 18, or 34 Mg ha^{-1} were topically applied to tobosagrass (*Hilaria mutica* (Buckl.) Benth.) experimental plots in a Chihuahuan desert grassland in western Texas. Biosolids were applied twice in 1994, for one-year-only, either in winter-and-summer (WS), or spring-and-summer (SS) seasons. Half of the plots were irrigated every summer for 4 years (1994-1997). Tobosagrass standing crop (herbage yield) and total Kjeldahl nitrogen concentration (plant %TKN) were measured every year during the 4 years of the study (1994-1997). An increase in biosolids rate increased tobosagrass herbage yield linearly during the 4 growing seasons. Linear and quadratic responses to biosolids rates were observed in %TKN during the experiment. Irrigation increased tobosagrass herbage yield. Irrigation decreased %TKN in 1995 and 1996 and had no influence during the other years. Winter-and-summer applications increased herbage yield more than spring and summer applications in 3 out of 4 years. Spring-and-summer applications increased %TKN more than winter and summer applications only in 1996. Carry-over effects on tobosagrass herbage yield and %TKN were observed in the second, third, and fourth growing seasons after biosolids application. Twice-a-year application of biosolids for 1-year-only offers an excellent means to improve tobosagrass productivity and forage quality.

Key Words: *Hilaria mutica*, Chihuahuan desert grassland, biosolids surface-application, biosolids land-application, irrigation, standing crop, forage quality, carry-over effects

Resumen

Escasa informacion existe acerca de los efectos de aplicaciones de biosolidos en diferentes epocas del año y sus efectos residuales en pastizales semiaridos. Cuatro niveles de biosolidos fueron superficialmente aplicados en dosis de 0 (control), 7, 18, o 34 Mg ha^{-1} en parcelas experimentales de zacate toboso (*Hilaria mutica* (Buckl.) Benth.) en un pastizal desertico del oeste de Texas. Los biosolidos fueron aplicados dos veces por año en 1994, por un año solamente, en invierno-y-verano (IV) o primavera-y-verano (PV). La mitad de las parcelas fueron irrigadas a traves de cada verano durante cuatro años (1994-1997). La produccion de forraje y la concentracion total de nitrogeno (CTN) del toboso fueron estimados durante los cuatro años del estudio (1994-1997). El incremento en los niveles de biosolidos aumento la produccion de toboso linearmente a traves de los cuatro años de estudio. Se observaron respuestas lineales y cuadraticas de CTN con las dosis de biosolidos a traves del experimento. Las parcelas irrigadas incrementaron la produccion de forraje. La irrigacion disminuyo CTN en 1996 y 1996, aunque no influyo en los demas años. Las aplicaciones de IV incrementaron la produccion de forraje sobre las aplicaciones de PV en tres de los cuatro años. Las aplicaciones de PV incrementaron CTN sobre las aplicaciones de IV solo en 1996. Se observaron efectos residuales de la aplicacion de biosolidos en produccion de forraje y CTN a traves de la segunda, tercera, y cuarta estaciones de crecimiento. La aplicacion de biosolidos dos veces al año en ambas estaciones (IV y PV) ofrece una excelente herramienta para el mejoramiento de la produccion y la calidad de forraje del zacate toboso.

Application of inorganic fertilizers to arid and semiarid rangelands is beneficial (Freeman and Humphrey 1956, Holt and Wilson 1961, Herbel 1963, Stroehlein et al. 1968, Dwyer 1971, Pieper et al. 1974, Stephens and Whitford 1993) but not practical because of high costs and lack of carry-over effects (Herbel 1963). Use of organic materials is promising since they can improve long-term physical, chemical, and biological processes in arid and semiarid soils (Khaleel et al. 1981, Fuller 1991, Day and Ludeke 1993), thereby improving plant growing conditions.

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Anaerobically digested biosolids is a by-product of wastewater treatment. Efficient biosolids disposal is needed since municipalities generate approximately 6.2 million dry Mg yr^{-1} of biosolids. Biosolids generation is expected to reach over 12.4 million dry Mg yr^{-1} by the end of the year 2000 (USEPA 1989).

Experimental results with biosolids topically applied once-a-year for 1-year-only at rates of 4 to 90 Mg ha^{-1} benefit soil physical, chemical, and biological properties and plant growth in arid and semi-arid grasslands (Fresquez et al. 1990, Harris-Pierce et al. 1993, 1995, Aguilar et al. 1994, Brenton 1995, Moffet 1997, Benton and Wester 1998, Pierce et al. 1998, Rostagno 1998). Current regulations for application of biosolids to cropland in Texas allow once-a-year application of 18 dry Mg ha^{-1} (Gass and Sweeten 1992). The Environmental Protection Agency (EPA) recommends an annual application rate (AAR) for domestic sewage application to land, forest, or reclamation site of AAR=1.121N/0.0026, where N=amount of nitrogen (kg/ha/yr) needed by vegetation grown on land (USEPA 1996).

Tobosagrass (*Hilaria mutica* (Buckl.) Benth.) is one of the dominant grasses in the northern Chihuahuan desert. It is a perennial, native, warm season grass, with good to fair forage value for livestock (Stubbendieck et al. 1992). Although tobosagrass forage productivity (Herbel 1963, Britton and Steuter 1983) and quality (Nelson and Johnson 1987, Brown and Houston 1993) are poor, they can be improved with increased soil fertility and moisture (Herbel 1963, Wright 1969, Britton and Steuter 1983).

There is no information on the forage yield and quality from twice-a-year, for 1-year-only, land application of biosolids to desert grasslands. Furthermore, there is little information on seasonal applications of biosolids and their carry-over effects on forage yield and quality of tobosagrass. This study was initiated to determine the effects of twice-a-year, for 1-year-only, application of biosolids on tobosagrass forage yield and nitrogen concentration.

Materials and Methods

Study Area

The study was conducted on the Sierra Blanca Ranch located 10 km north of Sierra Blanca, Texas (Hudspeth Co.)(Latitude 31° 16'N, Longitude 105° 22'W). Soils on the study site occur on planar slopes of the lower parts of an alluvial fan. Soils are deep, well drained, and are tentatively classified as Stellar taxadjunct very fine sandy loam, 1 to 3% slope, fine, mixed, thermic Vertic Paleargids (Casby-Horton 1997). The study site is on a Loamy (variant) Range Site. The vegetation is a Chihuahuan desert grassland, with tobosagrass, alkali sacaton (*Sporobolus airoides* (Torr.) Torr.), burrograss (*Scleropogon brevifolius* Phil.), and blue grama (*Bouteloua gracilis* (H.B.K.) Lag. ex Steud.) as common grasses. Honey mesquite (*Prosopis glandulosa* var. *glandulosa* Torr.) and lotebush (*Ziziphus obtusifolia* (T.&G.) Gray) are the most common shrubs. Domestic livestock, which grazed the site for at least 9 years prior to this research, were excluded since 1992.

Climate is a southwestern type (Holecheck et al. 1989), characterized by cool winters, dry hot springs, wet hot summers, and cool dry falls. Annual long-term precipitation averages 310 mm with 65% occurring between July and September (N.O.A.A. 1993, Fig. 1). Annual precipitation data from 1994 to 1997 were recorded by a weather station near the study site.

Treatments

Ninety-six experimental units (1m x 1m) were established in tobosagrass-dominated vegetation. Prior to biosolids application, biomass was harvested by hand-clipping all herbage at a 5-cm height in late December 1993. Plots were protected with poultry netting (60 cm tall, 5-cm mesh) to reduce lagomorph herbivory. A square plywood frame (70.71 x 70.71 x 10-cm) located in the center of each plot was used to retain biosolids on the plot area, and to define a vegetation sampling area of 0.5 m^2 within the frame.

Anaerobically digested municipal biosolids from New York City were provided by a commercial applicator on site for this study. Biosolids were applied twice in 1994, for 1-year-only, either in winter (11 January) and summer (8 July) seasons (WS), or in spring (16 April) and summer (8 July) seasons (SS), at rates of 0, 7, 18, or 34 dry Mg ha^{-1} per application. Therefore, a total of 0 (control), 14, 36, or 68 Mg $ha^{-1}yr^{-1}$ of biosolids were applied (on a dry weight basis) to the experimental units. For each biosolids application, 5 samples of fresh biosolids were randomly collected and frozen prior to shipment to New Mexico State University, Soil, Water, and Air Testing Laboratory for chemical analysis. Samples were oven dried for 24 hours at 60° C to determine biosolids moisture content. Biosolids were weighed in the field, applied topically, and hand-distributed uniformly throughout each plot according to season and rate of application.

Supplemental irrigation of 15 mm of water was provided manually with a sprinkler bucket early in the morning to half of the plots every 2 weeks during the growing season for each year of the study. A total of 75 mm of supplemental water was applied throughout the growing season each year. Nonirrigated plots were exposed to only natural rainfall conditions.

Aboveground tobosagrass standing crop (hereafter referred to as herbage yield) was harvested by hand-clipping all herbage at 5 cm above the soil surface at the end of each growing season. Herbage samples were oven-dried at 60ºC for 48 hours and weighed to the nearest 0.01 g to estimate herbage yield. Herbage samples were ground and passed through a 40 mesh screen in preparation for chemical analysis. Total Kjeldahl nitrogen concentration (%TKN) of each sample was determined (AOAC 1990) each year. A Tecator digestion system 40 (1016 Digester), along with a Tecator Kjeltec system 1026 distilling unit and a Mettler DL40RC titrator, were used for %TKN analysis.

Experimental Design and Data Analyses

A split plot arrangement of a completely randomized design was used for this study, with seasons of application (2 levels) as the main plot factor. Within each season of application, a factorial combination of 4 biosolids rates and 2 levels of irrigation were randomly assigned to individual 1-m^2 plots (subplots). There were 6 replications of each treatment for standing crop data, and 5 replications for plant nitrogen data. Years-after-application (4 levels) were analyzed as repeated measurements (sub-subplots).

Analysis of variance was used to test hypotheses of interest. The Shapiro-Wilk (1965) test was used to assess normality of main plot, subplot, and sub-subplot experimental errors. Levene's (1960) test was used to test for homogeneous variances in the main plot; Mauchley's (1940) test was used to test for sphericity in the subplot and sub-subplot portions of the analysis of variance. Herbage yield and %TKN data more closely satisfied assumptions for F tests when analyzed on a natural log-scale (Goodall 1970, Benton and Wester 1998). Although natural log-transformed data were analyzed, treatment means were back-transformed for data presentation; back transformed means are estimates of medians on the observed scale (Jager and Looman 1987). Adjusted F tests were used when sphericity was violated. Covariance analysis was performed in the first year for herbage yield data using initial biomass as a covariate to provide unbiased estimates of treatment effects.

Treatment mean separation was performed with the Fisher's Least Significant Difference (LSD) test for significant effects (Steel and Torrie 1980). Separate error terms were used for mean separation because of sphericity violation in the sub-subplot (Kirk 1995). Regression analysis was used to describe the response of tobosagrass herbage yield and %TKN to biosolids rate.

Results and Discussion

Biosolids Chemical Constituents

Biosolids moisture average was 71%. Although element concentrations varied among applications, concentrations for WS and SS averages were similar for most of the constituents analyzed (Table 1).

Precipitation

Precipitation amount and distribution varied greatly among the years of the

Table 1. Chemical composition of biosolids applied during winter, spring, or summer, 1994, Sierra Blanca, Texas.

Constituent	Winter 94 (n=2)	Spring 94 (n=5)	Summer 94 (n=5)	WS[1] Avg.	SS[1] Avg.
TKN(%)	3.36	2.92	3.62	3.49	3.27
P(%)	1.47	1.93	1.41	1.44	1.67
K(%)	0.68	0.09	0.04	0.36	0.06
Ca(%)	1.29	2.55	1.90	1.59	2.22
Mg(%)	0.44	0.91	0.38	0.41	0.65
Mn(mg kg^{-1})	544	1019	651	597	835
Zn(mg kg^{-1})	812	1147	1100	956	1123
Fe(mg kg^{-1})	23360	23092	19798	21579	21445
Cu(mg kg^{-1})	562	420	1033	797	726
B(mg kg^{-1})	34	33	33	33	33
Al(mg kg^{-1})	7531	7197	8279	7905	7738
Ni(mg kg^{-1})	26	43	22	24	32
Cd(mg kg^{-1})	8	9	8	8	8.5
Pb(mg kg^{-1})	212	321	187	199	254
EC[2](dS m^{-1})	14.0	-	11.6	12.8	11.6

[1]WS = Average of winter and summer; SS = Average of spring and summer.
[2]EC = Electrical conductivity.

study (Fig. 1). These differences influenced tobosagrass herbage yield and plant %TKN. Precipitation was about 30, 27, and 54% below the long-term average in 1994, 1995, and 1997, respectively, and approximately average in 1996.

Tobosagrass Herbage Yield

The response of tobosagrass herbage yield to biosolids depended on application rate ($P < 0.0001$, Fig. 2). However, rate of biosolids did not interact with years ($P>0.6135$) or with irrigation ($P > 0.6577$). A linear regression explained 93% ($P < 0.0001$) of the variation in the rate response. Herbage yield was similar between control and 7 Mg ha^{-1} rate. Herbage yield increased at 18 Mg ha^{-1} and 34 Mg ha^{-1} rates compared to the control rate (60 and 83%, respectively) and the 7 Mg ha^{-1} rate. Herbage yield was similar between 18 and 34 Mg ha^{-1} rates.

The beneficial response of tobosagrass herbage yield to twice-a-year, for 1-year-only, biosolids surface application indicates that biosolids improved plant growing conditions, including improved nutrient status. This agrees with research by Khaleel et al. (1981), Whitford et al. (1989), and Fuller (1991) where organic materials improved soil properties. The linear response of tobosagrass herbage yield to biosolids rate also suggests that desert grasslands are nutrient-limited environments (West and Klemmedson 1978). Some studies indicate that biosolids application can increase soil water availability by increasing water infiltration and reducing water runoff (Whitford et al. 1989, Aguilar et al. 1994, Harris-Pierce et al. 1995, Moffet 1997, Rostagno 1998).

In addition to their hydrological effects, biosolids may have supplied soil nutrients and organic matter that may improve soil chemical and physical properties (Seaker and Sopper 1988, USEPA 1989, Fresquez et al. 1990, Harris-Pierce et al. 1993, Aguilar et al. 1994, Brenton 1995, Moffet 1997, Rostagno 1998). Furthermore, biosolids could have increased soil microbial populations (Dennis and Fresquez 1989, Whitford et al. 1989, Fresquez and Dennis 1990, Strait 1996) because of their organic content, thus enhancing nutrient availability to plants. Hence, by improving hydrological, physical, chemical, and biological soil properties, biosolids may have acted both as fertilizer and soil conditioner in arid grasslands (Fresquez et al. 1990, Gass and Sweeten 1992).

Similar beneficial results in herbage yield of warm-season perennial grasses in semi-arid grasslands during the first growing season have been observed in field studies with 1-time surface-applied biosolids. For example, Fresquez et al. (1990) showed positive yield responses of blue grama and galleta (*Hilaria jamesii* (Torr.) Benth.) biosolids applied in the autumn at 22.5 to 90 Mg ha^{-1} on a degraded rangeland in New Mexico. Also, Harris-Pierce et al. (1993) found increased blue grama yield after summer application of biosolids from 4 to 34 Mg ha^{-1} in the shortgrass plains in Colorado. Benton and Wester (1998) also indicate increasing forage production in both tobosagrass and alkali sacaton with winter or summer application of biosolids from 7 to 90 Mg ha^{-1} in a desert grassland in western Texas. In contrast, Pierce et al. (1998) did not observe beneficial herbage yield effects of summer biosolids application from 5 to 40 Mg ha^{-1} on cool season perennial grasses such as western wheatgrass (*Agropyron smithii* Rydb.), bluebunch wheatgrass (*A. spicatum* (Pursh.) Scribn. & Smith), or Indian ricegrass (*Oryzopsis hymenoides* (R.& S.) Ricker.) in mountain sagebrush vegetation in Colorado during the first growing.

Tobosagrass herbage yield was greater ($P < 0.0001$) in irrigated plots (430 kg ha^{-1}) than in nonirrigated plots (262 kg ha^{-1}). This was expected since water is one of the most important limiting plant growth factors in arid and semiarid environments

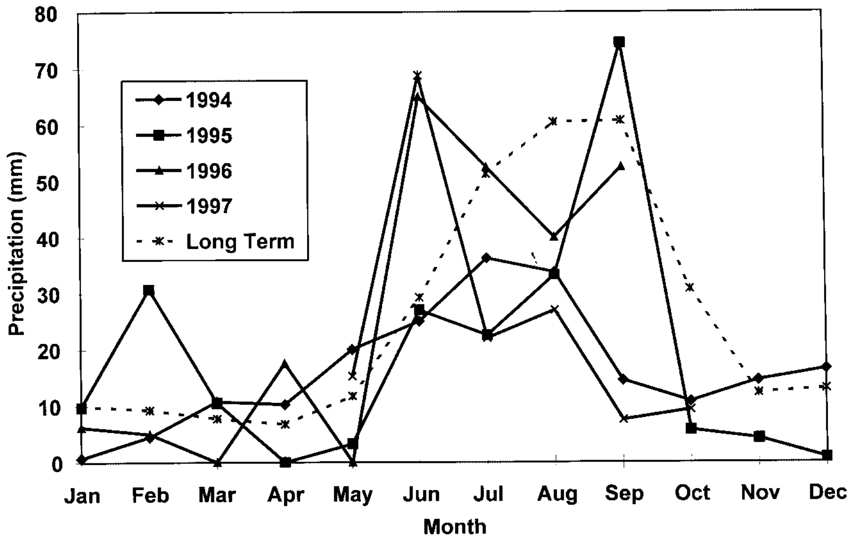

Fig. 1. Monthly precipitation throughout the 4 years of the study (recorded at the study site) and the long-term average precipitation (from N.O.A.A.) at Sierra Blanca, Texas. Missing data for early 1996, and early and late 1997.

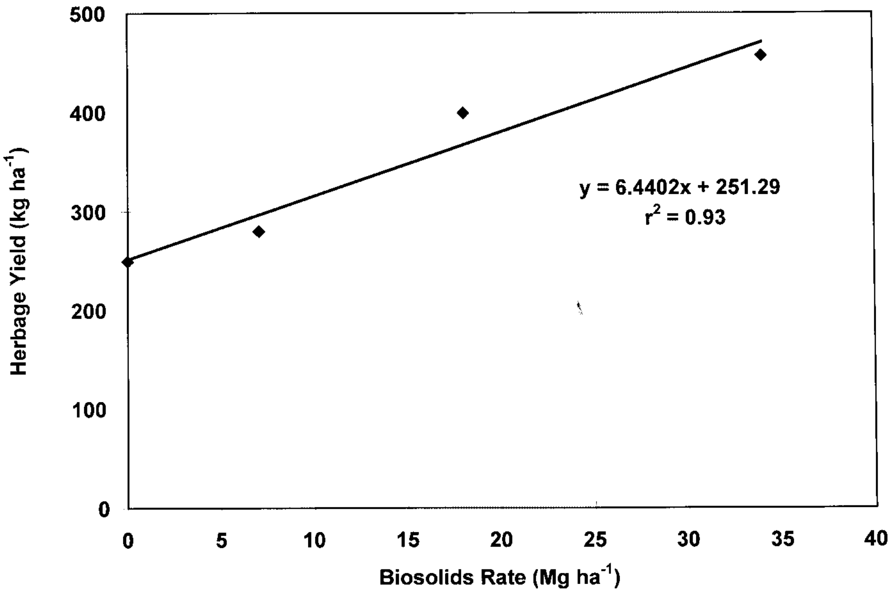

Fig. 2. Tobosagrass herbage yield response to biosolids application during the 4 years of the study (1994-1997). For rate comparisons, $LSD_{0.05}$ = 0.2314 (log scale) (n = 96).

(Noy-Meir 1973, Day and Ludeke 1993, Brown 1995), and summer rainfall was below normal during most of the years of the study. These results agree with other studies on the effects of irrigation on tobosagrass and alkali sacaton (Benton and Wester 1998), tobosagrass and blue grama (Cooley 1998), black grama (*Bouteloua eriopoda* (Torr.) Torr.) (Stephens and Whitford 1993), and fluffgrass (*Erioneuron pulchellum* (H.B.K.) Tateoka) (Ettershank et al. 1978) in Chihuahuan desert grasslands.

The significant main effects of biosolids rate and irrigation on herbage yield, together with the absence of an interaction between these 2 factors, do not support the "water limited-nutrient regulated" hypothesis of Ludwig et al. (1989) offered to explain the effects of water and nutrients on plant growth in Chihuahuan desert ecosystems. Instead, these results support a "water and nutrient limited" hypothesis (Benton and Wester 1998): although growth is limited by each of these resources, their effects evidently are not synergistic.

Also, tobosagrass herbage yield was affected by seasons of biosolids application, a factor that interacted with years-after-application ($P < 0.02$, Fig. 3). Winter and summer applications increased herbage yield more than spring and summer applications during the first, third, and fourth growing seasons after biosolids application in this study.

The greater response to winter and summer applications on tobosagrass herbage yield during the first growing season may be attributed to the improvement of plant growing conditions such as higher soil water availability and/or nutrient supply to the plants: these effects may have been initiated by the winter application in this treatment, providing a "headstart" effect for plants relative to later seasonal applications. The lower response to spring and summer applications can be attributed to below normal rainfall conditions after application (see Cooley 1998). Furthermore, spring and summer applications may have supplied less nitrogen to the soil because of potential ammonia volatilization losses from biosolids applied under warm conditions (Beauchamp et al. 1978, Harmel et al. 1997). Similar seasonal effects of biosolids applications on forage production were first reported by Benton and Wester (1998) under once-a-year topical application of biosolids at 7 to 90 Mg ha^{-1} in both tobosagrass and alkali sacaton herbage yield during the first growing season in desert grasslands. This effect was extended into the second growing season for alkali sacaton in their study.

The absence of seasonal effects on herbage yield in the second year (Fig. 3) of this study may be attributed to atypical growing conditions and to plant growth stage at the time of clipping. After a very dry early summer, a significant rainfall event (75 mm) in the middle of September stimulated late-season plant growth. Plots were clipped 1 month afterward when plants were still in the early stage of vegetative growth. Under these growing conditions, it is likely that effects of seasonal biosolids applications were similar.

The beneficial effect of winter and summer applications on herbage yield during the third growing season (Fig. 3) may be attributed to the initial effect of winter and summer applications that improved plant growth conditions. The same effect was also observed in the fourth growing season (1997) even under dry conditions. This may be related to previous favorable

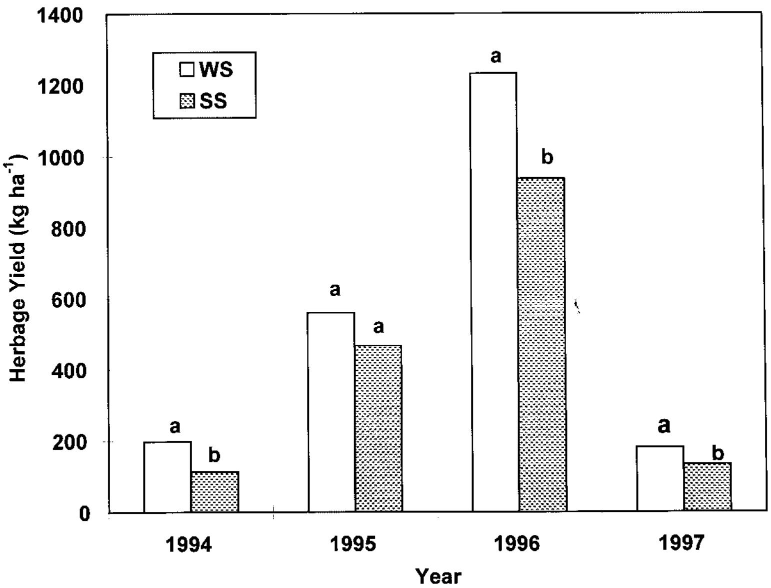

Fig. 3. Tobosagrass herbage yield response to seasons of biosolids application and years-after-application of biosolids. Treatments were applied in winter-and-summer (WS) or spring-and-summer (SS), 1994. Treatments with different letters within a year are significantly different ($P < 0.05$).

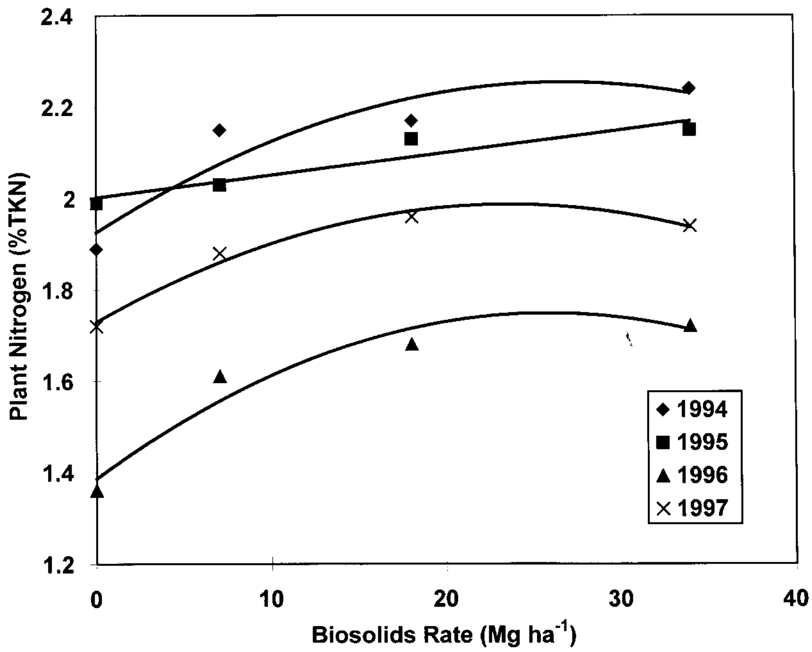

Fig. 4. Tobosagrass total nitrogen concentration (%TKN) response to biosolids rates and years-after-application of biosolids. In 1994: $Y = 1.9262 + 0.0245X - 0.0005X^2$, $R^2 = 0.86$. In 1995: $Y = 2.0028 + 0.0049X$, $R^2 = 0.85$. In 1996: $Y = 1.3862 + 0.0281X - 0.0005X^2$, $R^2 = 0.92$. In 1997: $Y = 1.7297 + 0.0219X - 0.0005X^2$, $R^2 = 0.97$. For rate comparisons, $LSD_{0.05} = 0.068$, 0.056, 0.055, and 0.064 on a log scale from 1994 to 1997, respectively. Plant N was measured at the end of each growing season.

growing conditions in 1996. However, mechanisms by which winter and summer applications increased herbage yield more than spring and summer applications are unknown.

Tobosagrass Total Nitrogen Concentration

Although the response of plant %TKN to biosolids application depended on biosolids rate, this effect interacted with years-after-application ($P < 0.0093$, Fig. 4). In general, %TKN increased with biosolids rate. In 1994, a quadratic regression explained 86% of the rate response. All biosolids rates increased %TKN compared to the control treatments. In 1995, %TKN increased with biosolids in a linear fashion ($r^2 = 0.85$). Tobosagrass total nitrogen concentration increased at 34 Mg ha^{-1} compared to 7 Mg ha^{-1} and control rates. Total nitrogen concentration was similar between 18 and 34 Mg ha^{-1} and between 7 Mg ha^{-1} and control rate. In 1996, a quadratic equation explained 92% of the variation in %TKN. Tobosagrass total nitrogen concentration increased at 18 and 34 Mg ha^{-1} rates compared to the control rate. Total nitrogen concentration increased at 7 and 18 Mg ha^{-1} rates compared to the control rate. Tobosagrass total nitrogen concentration was similar between 7 and 18 Mg ha^{-1} rates, and between 18 and 34 Mg ha^{-1} rates. In 1997, %TKN increased with biosolids rate with a quadratic response with an $r^2 = 0.97$. Total nitrogen concentration increased at all biosolids rates compared to the control rate.

The increase in plant %TKN suggests an increase in plant available nitrogen in the soil. These beneficial effects on plant quality with biosolids application have also been observed by Harris-Pierce et al. (1993) in blue grama nitrogen throughout 1 growing season after biosolids application; by Aguilar et al. (1994) in blue grama nitrogen after 2 growing seasons of biosolids application; and by Wester et al. (unpublished data) in tobosagrass throughout 2 growing seasons after application. Western wheatgrass, a cool-season grass, also showed an increase in plant tissue nitrogen concentration after 1 year of biosolids application in Colorado (Pierce et al. 1998).

The response of plant %TKN to biosolids also depended on irrigation. However, irrigation interacted with years-after-application ($P < 0.0001$, Fig. 5). Total nitrogen concentration was similar between non-irrigated and irrigated treatments in dry years (1994 and 1997), and decreased with irrigation in closer to normal precipitation years (1995 and 1996). This could be attributed to plant physiological mechanisms of tobosagrass in response to growing conditions, or the so called "dilution" effect of Black and Wight (1979).

The response of plant %TKN to biosolids also depended on seasons of application. However, seasons interacted

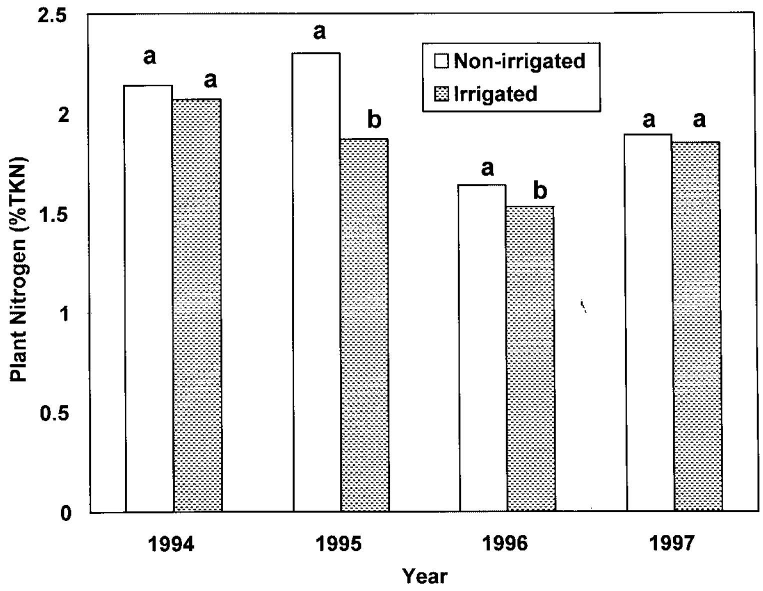

Fig. 5. Tobosagrass total nitrogen concentration (%TKN) response to irrigation and years-after-application of biosolids. Treatments with different letters within a year are significantly different ($P < 0.05$).

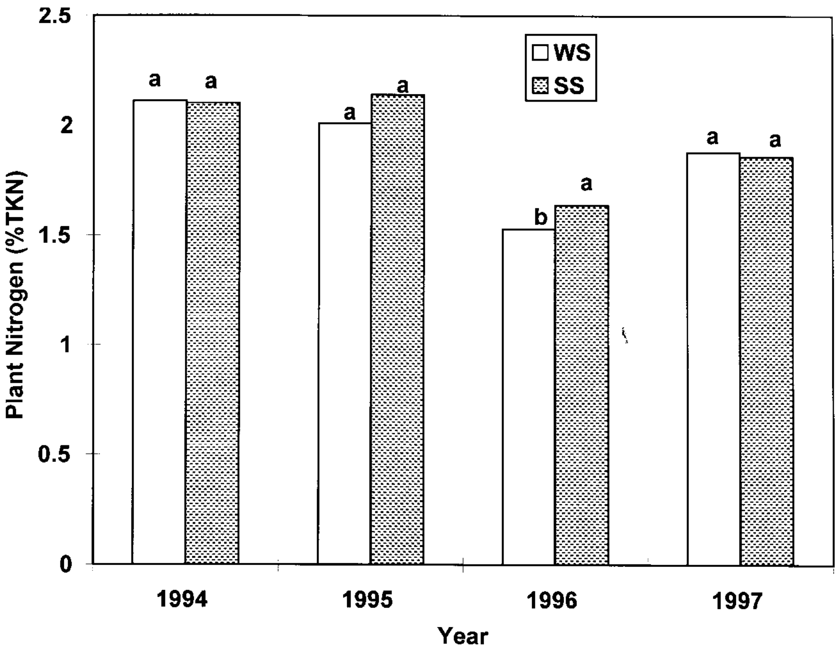

Fig. 6. Tobosagrass total nitrogen concentration (%TKN) response to seasons of biosolids application and years-after-application of biosolids. Treatments were applied in winter-and-summer (WS) or spring and summer (SS), 1994. Treatments with different letters within a year are significantly different (P < 0.05).

with years-after-application ($P < 0.01$, Fig. 6). Total nitrogen concentration was similar between winter and summer and spring and summer applications in most years (1994, 1995, and 1997). Tobosagrass total nitrogen concentration decreased with winter-summer applications compared to spring-summer treatments in 1996. These results could be related to the "dilution" effect (Black and Wight 1979) since higher herbage yield under winter and summer applications produced lower %TKN, and spring-summer applications had lower herbage yield and higher %TKN. However, the mechanisms of the seasonal effects of biosolids application on %TKN are unknown. These mechanisms could also be related to physical and/or chemical effects of biosolids on soil properties and to plant physiological factors.

Biosolids Carry-Over Effects

The absence of a rate by years-after-application interaction suggests a strong carry-over effect in herbage yield into the second, third, and fourth growing seasons in this study. Biosolids applied at 18 and 34 Mg ha^{-1} provided similar beneficial effects in both dry and normal years for four growing seasons after application in this study. This indicates a long-term and consistent beneficial effect of biosolids on tobosagrass herbage yield. Similar results were observed by Fresquez et al. (1990) on the response of blue grama herbage yield to a single summer biosolids application of 22.5 and 45 Mg ha^{-1} throughout four growing seasons and by Benton and Wester (1998) with once-a-year winter or summer biosolids rates at 18 or 34 Mg ha^{-1} throughout a 4-year study in alkali sacaton herbage yield.

Carry-over effects on herbage yield after biosolids application have also been observed into the third growing season by Cooley (1998) under once-a-year biosolids rates at 34 Mg ha^{-1} on blue grama attributed to a normal precipitation growing season. Benton and Wester (1998) also showed carry-over effects on tobosagrass production at 7, 18, and 34 Mg ha^{-1} in a desert grassland in western Texas and Pierce et al. (1998) documented carry-over effects with 1-time biosolids topically-applied up to 40 Mg ha^{-1} to cool-season perennial grasses in Colorado. In contrast, no carry-over effects during the second growing season on galleta herbage yield (Fresquez et al. 1990), blue grama standing crop (Cooley 1998), or tobosagrass herbage yield (Benton and Wester 1998) were observed in once-a-year biosolids applications because of dry growing season conditions.

Carry-over effects of biosolids on %TKN into the second growing season were observed by Aguilar et al. (1994) with 1-time biosolids topically-applied at 45 Mg $ha^{-1}yr^{-1}$ to blue grama in semiarid rangelands in New Mexico and by Wester et al. (unpublished data) in tobosagrass nitrogen after 2 growing seasons with autumn applications of biosolids in western Texas. Pierce et al. (1998) also observed carry-over effects on plant nitrogen concentration into the second and fifth growing seasons on cool-season grasses in Colorado.

These carry-over effects in both herbage yield and %TKN could be attributed to the beneficial impact of biosolids on soil fertility that may last for several years (White et al. 1997). Carry-over effects in herbage yield were always present with twice-a-year biosolids application from 18 to 34 Mg ha^{-1} regardless of dry or normal growing conditions in this study. However, carry-over effects in %TKN apparently depended on growing conditions. The long-term beneficial effects of biosolids will eventually disappear as indicated by White et al. (1997), who did not observe soil or plant quality beneficial effects after 8 years of biosolids application to blue grama on a semiarid rangeland in New Mexico.

Conclusions

Twice-a-year biosolids surface application for 1-year-only increased herbage yield and plant %TKN. Herbage yield increased linearly with increasing biosolids rates during the 4 years of the study. Supplemental irrigation also increased tobosagrass herbage yield during the study. In general, winter and summer applications had more beneficial effects on herbage yield than spring and summer applications, except in 1995 (a year with atypical rainfall distribution). Plant %TKN increased (at a decreasing rate) in three out of four years of this study as a result of biosolids application. Irrigation did not affect %TKN in dry years, and decreased %TKN in wetter years. In general, seasons of biosolids application benefited %TKN similarly, except in 1996 (a normal rainfall year) where spring and summer applications increased %TKN compared to winter and summer applications.

These results suggest that biosolids application has a beneficial effect on tobosagrass herbage yield, and plant nitrogen concentration. Thus, biosolids application in this ecosystem may be beneficial for waste disposal and rangeland improvement.

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