Colegio de Postgraduados

Improvement of degraded grasslands with biosolids application in a semiarid region of Chihuahua, Mexico

Jurado-Guerra, Pedro[1]; Royo-Márquez, Mario H.[1]; Morales-Nieto, Carlos R.[2]; Ramírez-Garduño, Héctor[1*]

[1] Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias. Campo Experimental la Campana. Km 33.3 Carretera Chihuahua-Ojinaga. Aldama, Chihuahua, México. C. P. 32910.
[2] Universidad Autónoma de Chihuahua. Facultad de Zootecnia y Ecología. Periférico R. Almada Km 1. Chihuahua, Chihuahua, México. C.P. 31453.
[*] Correspondence: ramirez.hector@inifap.gob.mx

ABSTRACT

Objective: to evaluate the influence of surface-applied anaerobic biosolids on forage production and grass basal cover of a degraded grassland in the semiarid region of Chihuahua, Mexico.

Design/methodology/approach: The study was conducted in a degraded grassland in a semiarid region in Chihuahua, Mexico. Six biosolids rates from 0 to 50 Mg ha^{-1} were evaluated in field plots with six replications. A completely random design was used for the study. Anaerobic biosolids from Chihuahua City were applied to field plots in March 2005. Soil properties were analyzed in 2005. Plant height was measured during the summer. Basal plant cover and standing crop were estimated at the end of the growing season for four years. Analysis of variance was performed with mixed models and repeated measures.

Results: Soil organic matter, plant available nitrogen, height of blue grama (*Bouteloua gracilis*) and other grasses increased with biosolids application. Total forage and blue grama forage yield increased, but other grasses decreased their forage production during the four years. Basal cover of perennial grasses was not affected during the first two years, but decreased in the last two years with heavy rates.

Limitations on study/implications: Biosolids transportation and application represent a high initial investment.

Findings/conclusions: Biosolids application improved soil organic matter, plant-available nitrogen, and total forage standing crop. Basal cover of grasses was not affected at low biosolids rates and decreased under heavy biosolids rates.

Keywords: organic amendments, forage yield, soil organic matter, plant-available nitrogen, plant cover.

Citation: Jurado-Guerra, P., Royo-Márquez, M. H., Morales-Nieto, C. R., & Ramírez-Garduño, H. (2025). Improvement of degraded grasslands with biosolids application in a semiarid region of Chihuahua, Mexico. *Agro Productividad*. https://doi.org/10.32854/n2vxdj11

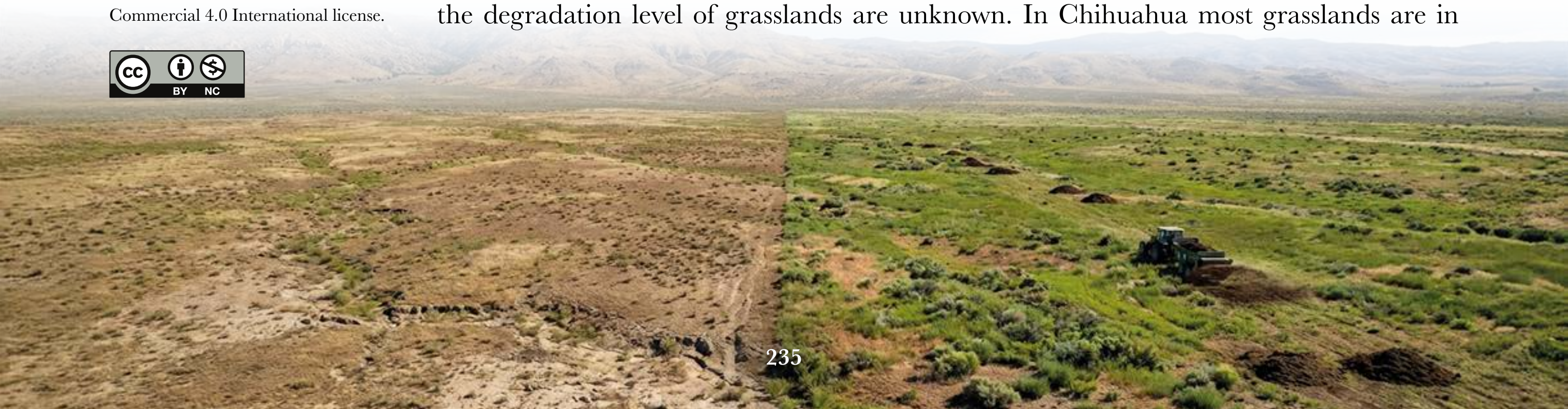
Academic Editor: Jorge Cadena Iñiguez
Associate Editor: Dra. Lucero del Mar Ruiz Posadas
Guest Editor: Daniel Alejandro Cadena Zamudio

Received: June 11, 2025.
Accepted: October 14, 2025.
Published on-line: December XX, 2025.

Agro Productividad, 18(11). November. 2025. pp: 235-245.

INTRODUCTION

In the semiarid region of northern Mexico, native grasslands are essential for extensive beef cattle ranching, and they simultaneously provide environmental services and recreational activities to society. Unfortunately, 95% of grasslands have been overgrazed and show different stages of degradation (SEMARNAT, 2016), although precise data on the degradation level of grasslands are unknown. In Chihuahua most grasslands are in



moderate-extreme to extreme rangeland health and need improvement techniques to recover their functionality (Royo *et al.* 2005).

Degraded grasslands require improvement techniques such as grazing management, brush management, fertilization, or prescribed burns to recover their structure and functionality. Fertilization is an expensive practice, and it is recommended only in areas with good soil and precipitation. As an alternative, the application of organic amendments or byproducts has gained attention. Organic amendments such as biosolids enhance soil properties, forage quantity, and quality of semiarid grasslands (Wester *et al.*, 2011; Ploughe *et al.*, 2021).

Biosolids are stabilized organic byproducts of wastewater treatment plants, used as an organic amendment for soil due to their high organic matter and nutrient content (SEMARNAT, 2003), and their generation in Mexico is about 640 million Mg yr^{-1} (Mantilla *et al.*, 2017). A recent meta-analysis reported that biosolid application increases productivity and cover, but did not affect species diversity of degraded grasslands (Ploughe *et al.*, 2021). Wallace *et al.* (2016) also indicated a positive influence of biosolids on soil fertility, although they did not observe benefits on perennial grasses growth in a semiarid grassland. Additionally, biosolids application has increased corn grain and forage production, survival, and growth of forest plantations (Salcedo-Pérez *et al.*, 2007).

Several studies have documented the benefits of biosolids application, including increases in soil water infiltration on west Texas grasslands (Rostagno & Sosebee, 2001; Jurado *et al.*, 2007); higher soil fertility in arid grasslands in Texas (Jurado-Guerra *et al.*, 2006; Jurado *et al.*, 2007); higher grass forage standing crop of tobosagrass (*Hilaria mutica* (Buckley) Benth.) in Texas (Jurado & Wester, 2001; Mata-González *et al.*, 2002) and blue grama (*Bouteloua gracilis* (Kunth) Lag. ex Griffiths) in Jalisco, Mexico (Jurado *et al.*, 2006) and boer lovegrass (*Eragrostis curvula* (Schrad.) Nees) in Sonora (Martin *et al.*, 2019). However, some adverse effects have also been reported with biosolids application, such as reduced plant diversity and richness in grasslands of New Mexico (Fresquez *et al.*, 1990) and Spain (Martinez *et al.*, 2003).

Limited research has been conducted on the effects of biosolids on degraded grasslands in northern Mexico. In fact, biosolids production in wastewater plants in Chihuahua and other cities of Northern Mexico is increasing, and no beneficial use of them has been reported. We hypothesized that biosolids enhance soil properties and increase grass growth in semiarid conditions. The objective was to evaluate the influence of surface-applied anaerobic biosolids on selected soil properties, forage production, and grass basal cover of a degraded grassland in the semiarid region of Chihuahua, Mexico.

MATERIALS AND METHODS

The study was carried out at Ejido Nuevo Delicias, Chihuahua, located 75 km north of Chihuahua City (29° 12' 02" N, 106° 24' 43" O). The study site belongs to the "Sierras y Llanuras del Norte" Province and the "Bolson de Mapimi" subprovince at 1,640 masl (INEGI, 2010). The climate is dry with summer rainfall, a mean annual temperature of 16 °C, and a mean annual rainfall of 350 mm (INEGI, 2010). Soils are colluvial-alluvial with a sandy loam texture. The original vegetation was an open grassland with *Bouteloua-Aristida*

(COTECOCA, 1978), and has been recently invaded by broom snakeweed (*Gutierrezia sarothrae* (Pursh) Britton & Rusby), catclaw (*Mimosa dysocarpa* Benth.), and mesquite (*Neltuma glandulosa* (Torr.) Britton & Rose).

Thirty-six field plots at 2.44 m×2.44 m (5.9 m^2) size were established in January 2005. A 10-cm tall plywood was used to mark field plots and pushed down within the soil to prevent biosolids movement out of the plots. The initial basal cover of perennial grasses was estimated at two permanent 2 m transects per plot in early March 2005. Initial forage standing crop was not estimated since stubble height was close to the ground due to overgrazing.

Domestic anaerobic biosolids from the North Wastewater Treatment Plant in Chihuahua City were used for the study. Six 1 kg biosolids samples were taken from different parts of the pile, and a composite sample was taken for chemical analysis (Table 1). The following parameters were analyzed: pH ($CaCl_2$/electrometric pH meter); organic matter (OM) (Walkley and Black); electrical conductivity (EC) (saturated paste/Solu-bridge); extractable nitrate-nitrogen (NO_3-N) (Brucina and Colorimetric method); extractable Phosphorus (Bray-P1); Potassium, Calcium, Magnesium, and Sodium extracted by Ammonium acetate; Copper, Manganese, Iron, and Zinc extracted by DTPA and analyzed by Atomic Absorption Spectroscopy. Lead, Nickel, Chromium, and Cadmium were extracted by acid digestion and analyzed by Flame Atomic Absorption Spectroscopy (FAAS). Arsenic and Mercury were analyzed using FAAS and a hydride generator system. Biosolids analyses were done according to the Mexican Official Standards "NOM-004-SEMARNAT-2002" (SEMARNAT, 2003).

Biosolids moisture content was determined gravimetrically from six 50 gr subsamples, resulting in 77.9%. Then, they were applied according to their moisture content and plot size at 0 (control), 10, 20, 30, 40, or 50 Mg ha^{-1} rates with six replications in mid-March 2005. Biosolids were surface-applied dry and distributed manually with a rake

Table 1. Composition of domestic anaerobic biosolids from the North Wastewater Treatment Plant at Chihuahua City, Mexico. March 2005.

Parameter	Concent.	Element	Concent.
pH	6.7	Cu	9
TOM[a](%)	12	Fe	30
TCC(%)	Free	Mn	15
EC(dS m^{-1})	3	Zn	111
N-NO_3	66	Pb	84
P	7.1	Ni	20
K	962	Cd	5
Ca	3,412	Hg	3
Mg	1,037	As	2
Na	1,312	Cr	155

[a] TOM=Total organic matter; TCC=Total calcium carbonate; EC=Electrical conductivity; N-NO_3 and elements from P to Cr are extractable and expressed on a dry weight basis in mg kg^{-1}.

within each plot. The study area was excluded from grazing with a fence and poultry netting. Rainfall was measured on-site during four growing seasons (Figure 1) with a 6-in rain gauge.

We collected soil samples at 0-15 cm depth in August 2005, and selected soil properties were analyzed according to the Mexican Official Standards "NOM-021-SEMARNAT-2000" (SEMARNAT, 2002). Plant height of the more common grass species was estimated in August 2005. At the end of each growing season in November of each year, the basal cover of perennial grasses at the permanent transects and forage standing crop by clipping were estimated over four years. Forage standing crop was estimated by clipping grasses manually at a 5 cm stubble height in all plots, separating dominant species such as blue grama, hairy grama (*Bouteloua hirsuta* Lag.), and other perennial grasses. Forage samples were dried to a constant weight and converted to Mg ha^{-1}.

A completely randomized design was used for the study (Kirk, 1982). Analyses of soil properties and plant height were done with "Proc Anova" (SAS, 2011). Forage standing crop responses to biosolids were performed through linear mixed models using the "Proc Mixed" procedure and repeated measures (SAS, 2011). Several covariance structures were evaluated to fit the best model for forage production data. The best model was the one with unstructured variance, showing the smallest Akaike Information Criterion (AIC). Statistical effects were significant at P=0.05, and mean separation was performed by the LSD test. Trend analyses of forage production were conducted to detect the response to biosolids rates and year.

RESULTS

Soil Properties

The application of biosolids significantly increased soil organic matter (P<0.0080), starting at 0.25% at the control rate and increasing to a maximum of 0.47% at 20 Mg ha^{-1} rate (Table 2). Available nitrogen was also affected (P<0.0018) by biosolids application (Table 2), increasing with biosolids rate. However, biosolids did not significantly influence

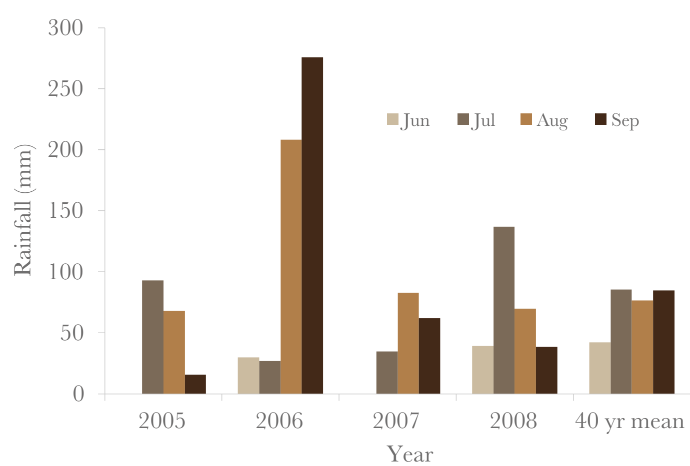


Figure 1. Monthly rainfall from 2005 to 2008 and 40 yr mean from 1961 to 2003 according to Medina *et al.* (2006) at the study site. Ejido Nuevo Delicias, Chihuahua, Mexico.

Table 2. Chemical soil properties at 0-15 cm depth (mean±SE) as affected by biosolids rate on a degraded semiarid grassland in Chihuahua, Mexico.

Biosolids rate (Mg ha^{-1})	SOM (%)	NO_3-N (mg kg^{-1})
0	0.25±0.03 b	10.1±3.2 c
10	0.39±0.03 a	12.8±3.2 bc
20	0.47±0.03 a	15.0±3.2 bc
30	0.40±0.03 a	13.8±3.2 bc
40	0.38±0.03 a	19.5±3.2 b
50	0.40±0.03 a	30.5±3.2 a

SOM=Soil organic matter. SOM or NO_3-N means within biosolids rate, followed by the same letter are not significantly different (P>0.05).

soil pH (P>0.4109; mean±se=4.99±0.13), electrical conductivity (P>0.1271; 0.59±0.11 dS m^{-1}), available phosphorus (P>=0.1158; 19.3±3.9 mg kg^{-1}), and potassium (P>0.8900; 150±18 mg kg^{-1}).

Plant Height

Biosolids increased plant height of blue grama (P<0.0001) from 25±5 cm at control rate to 54±11 cm at 20 Mg ha^{-1} with a 116% increment (Figure 2). However, hairy grama height was not affected (P>0.1123) by biosolids with a mean of 37±5 cm. Also, three awn grass (*Aristida ternipes* Cav.) was influenced by biosolids (P<0.0005), 27±6 cm at control rate to 50±5 cm with 20 Mg ha^{-1} with 85% increase (Figure 2).

Forage Production

Total forage production of perennial grasses was significantly affected by a biosolids rate×year interaction (P<0.0001), ranging from a minimum of 198±36 kg ha^{-1} at 50 Mg ha^{-1} in 2007 to a maximum of 2,764±475 kg ha^{-1} at 50 Mg ha^{-1} in 2006 (Figure 3). Forage production increased with most biosolids rates during 2005, 2006, and 2008, with a more pronounced effect on 2006, showing a seven-fold increase on forage production

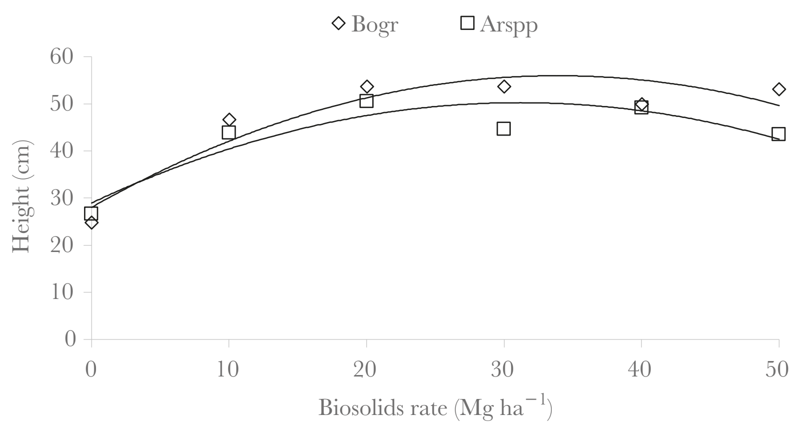


Figure 2. Plant height of blue grama grass (Bogr) and three-awn grass (Arspp) under biosolids application in a semiarid grassland in Chihuahua, Mexico.

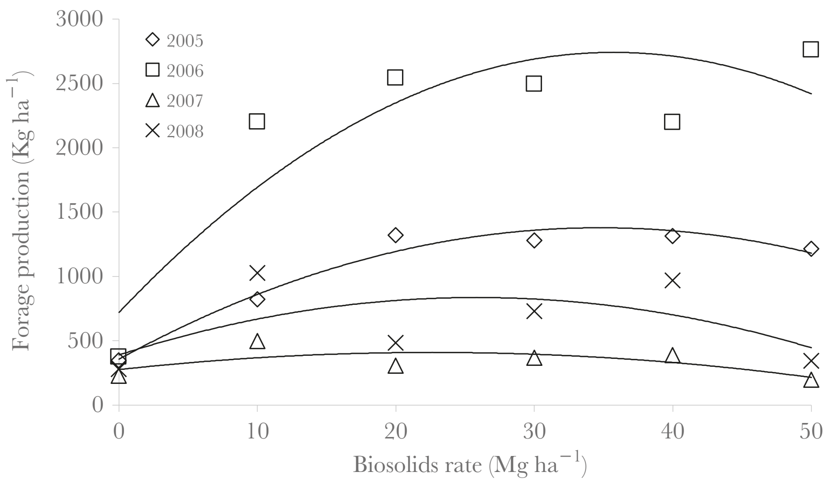


Figure 3. Forage standing crop as affected by biosolids rate and year on a semiarid grassland in Chihuahua, Mexico.

compared to the control. In 2007, biosolids application only showed a slight beneficial effect on the 10 Mg ha^{-1} rate. Overall, biosolids rates from 10 to 40 Mg ha^{-1} showed the best results on forage production across most years (Figure 3).

Analysis of forage production by species revealed interesting shifts in species composition. Blue grama forage comprised 16% of the total forage at control rate in 2005, increasing at all rates up to a maximum of 62% of the total forage at 10 Mg ha^{-1} biosolids rate. Conversely, hairy grama forage decreased at all rates from 21% to a minimum of 9% of the total at control rate to 20 Mg ha^{-1} rate, respectively, in 2005. Other perennial grasses, mainly three awns, sideoats grama (*Bouteloua curtipendula* (Michx.) Torr.), and sand dropseed (*Sporobolus cryptandrus* (Torr.) A. Gray) initially accounted for 62% of the total forage production at control rate in 2005, decreasing at all rates to a minimum of 21% at the 10 Mg ha^{-1} rate. In 2006, a wet year, blue grama forage production was 43% in the control rate, and decreased to 12% in the 20 Mg ha^{-1}. Hairy grama decreased extremely from 26% in the control rate to 0.1% in the 20 Mg ha^{-1} rate, while other grasses increased from 31% to a maximum of 88% of the forage production. In 2007, a dry year, forage production of blue grama only increased to 51% at the 10 Mg ha^{-1} rate, and was similar among the other biosolids rates. Hairy grama forage production decreased from 15% at control rate to a minimum of 2% at the 20 Mg ha^{-1} biosolids rate. Other grasses, including three awns, remained similar among biosolids rates. After four years of application, blue grama remained at 14% of the total forage at the control rate in 2008, increasing at all biosolids rates up to a maximum of 61% of the total forage production at 40 Mg ha^{-1} rate. Similarly to the rest of the years, hairy grama decreased with biosolids application from 39% of the forage at control rate to a minimum of 4% at the 40 Mg ha^{-1} rate in 2008. Other grasses like three awns, sideoats grama, and carolina crabgrass (*Digitaria cognata* (Schult.) Pilg.) composed 47% of the forage at the control rate in 2008, slightly decreasing at all biosolids rates to a minimum of 34% at 10 Mg ha^{-1} rate.

Plant Basal Cover

Initial basal cover of perennial grasses before biosolids application was similar ($P>0.3347$) among all plots, with a 7.04±0.16% (mean±se), so changes of cover in the following years may be attributed to biosolids application. In general, basal cover was influenced by biosolids rate ($P<0.0001$), year ($P<0.0001$), and rate×year interaction ($P<0.0002$) (Figure 4), and ranged from 1.52% at 50 Mg ha^{-1} in 2008 to 14.41% at 20 Mg ha^{-1} in 2005. In 2005 and 2006, basal cover slightly increased at 10 and 20 Mg ha^{-1}, compared to control rate. However, cover remained similar among control rate and the other biosolids rates. Basal cover at both 2007 and 2008 decreased with increasing biosolids rate, ranging from 10.3±0.84% at control rate to 2.56±1.1% at 50 Mg ha^{-1} rate, and from 13.6±1.1% at control rate to 1.52±1.1% at 50 Mg ha^{-1} rate, respectively (Figure 4).

DISCUSSION

Soil Properties

The increase of soil organic matter and plant-available nitrogen in the soil observed in this study was the result of biosolids application that provided nutrients to the soil, such as nitrogen and phosphorus (Jurado-Guerra *et al.*, 2006; Potisek-Talavera *et al.*, 2010), enhancing plant growing conditions by promoting water infiltration and retention (Rostagno & Sosebee, 2001; Jurado *et al.*, 2007). These results agree with other studies that have benefited soil fertility in semiarid grasslands *et al.*, 2007; Ippolito *et al.*, 2010; Wallace *et al.*, 2016). Beneficial effects of biosolids were also observed by Lara-Villa *et al.* (2022), indicating increases of soil nitrate-nitrogen under winter-and summer application of low rates in a semiarid shrubland of central Mexico.

Forage Production and Plant Height

Favorable results of biosolids application on grass forage growth can be attributed to the improvement of plant growing conditions such as higher soil water infiltration, available

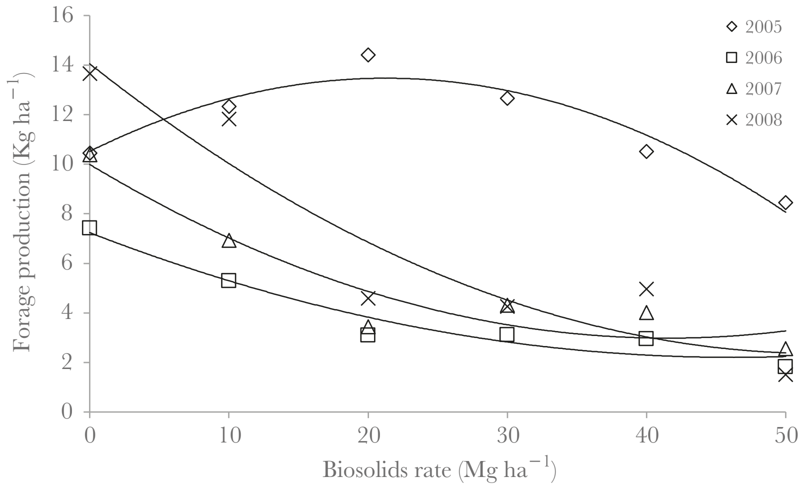


Figure 4. Basal cover of perennial grasses as affected by biosolids application and year on a degraded semiarid grassland in Chihuahua, Mexico.

soil moisture, and available soil nitrogen observed in several studies in arid and semiarid grasslands (Rostagno & Sosebee, 2001; Jurado-Guerra *et al*., 2006; Jurado *et al*., 2007). Similar responses in forage standing crop increases have been documented with surface-applied biosolids on tobosagrass in Texas desert grasslands (Jurado & Wester, 2001) and on blue grama in semiarid grasslands of central Mexico (Jurado *et al*., 2006). Several authors have also observed long-term effects of biosolis application on forage production of semiarid grasslands (Jurado *et al*., 2013; Avery *et al*., 2019). According to this, a recent meta-analysis indicates that biosolid application increases productivity of grasslands (Ploughe *et al*., 2021). Lara-Villa *et al*. (2022) observed the beneficial effects of biosolids, indicating increases of perennial grasses forage under winter-and-summer application of low rates in a semiarid shrubland of central Mexico. Martin *et al*. (2019) also reported a two-fold increase in forage production of exotic boer lovegrass with biosolids application, with a high potential to increase stocking rate.

The variation in forage production among years may be attributed to differences in rainfall. As expected, forage production increased in wet years like 2006, showing 87% above the mean rainfall. Conversely, forage production was low in 2007, a dry year, with almost 40% below the precipitation mean. This pattern is consistent with the positive relationship between rainfall and plant productivity (Kramer, 1983; Barbour *et al*., 1987). Then, biosolids rates higher than 10 Mg ha^{-1} showed no effect compared to the control at forage production in dry years. This effect may be related to a study where fertilization of arid grasslands in China increased soil nitrogen and phosphorus concentration in wet years, but these effects did not occur in dry years (Ren *et al*., 2018).

Composition of forage species production changed with biosolids application. This effect could be explained by different responses of each grass species to resource availability as well as to interspecific species competition as indicated by several authors (Tilman, 1987; Wilson and Tilman, 1993) in competition studies among grasses. A recent study also indicated that biosolids can change the long-term plant composition by increasing the presence of exotic grasses like Kentucky bluegrass (*Poa pratensis*) (Avery *et al*., 2019). Conversely, Ploughe *et al*. (2021) concluded that biosolids application on grasslands did not influence species richness or plant diversity.

Plant Basal Cover

Biosolids application did not change basal cover during the two years of application, but it decreased in the following two years. No studies have reported results of biosolids application on basal cover. Ippolito *et al*. (2010) reported an increase of plant canopy cover, different from basal cover, with biosolids application on a semiarid short-grass rangeland in Colorado. Ploughe *et al*. (2021) also reported that biosolids increased plant cover in grasslands, although they did not specify if it was basal or canopy cover.

Despite positive results on semiarid grasslands, biosolids application on degraded rangelands faces two major challenges: public acceptance due to their origin and odor, and high transportation costs. The public might accept biosolids through composting alone or mixed with other materials (Tognetti *et al*., 2007). On the economics of biosolids application on grasslands, there is limited information, however, studies on wheat cultivation indicate that the optimal level of biosolids application is 7.3 Mg ha^{-1} with a cost of application of \$4.00 dollars Mg^{-1} (Lagae *et al.*, 2009). Martin *et al.* (2019) analyzed the cost of biosolids application on grasslands of Sonora and concluded that real profits start after the fourth year, because of the initial investment for transportation and land application. However, other authors indicate that the economic feasibility of biosolids application not only depends on transportation costs, but also on other factors like the treatment of biosolids and the legal framework (Elgarahy *et al.*, 2024).

CONCLUSIONS

Biosolids had favorable effects on selected soil properties such as organic matter and nitrate-nitrogen. Blue grama forage production also benefited from biosolids application at all rates. Other grasses such as hairy grama, three awn, sideoats grama, sand dropseed, and Carolina crabgrass were negatively affected by biosolids.

The favorable effects of biosolids were observed mainly on normal to above-normal precipitation years. Forage production of perennial grasses was not affected by biosolids in dry years. Biosolids rates at 10-20 Mg ha^{-1} showed the best results on forage production without a negative effect on basal cover of grasses.

ACKNOWLEDGMENTS

Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (INIFAP) for financial support. Héctor Domínguez Caraveo and Efraín Valverde for their help on the field.

REFERENCES

Avery, E., Krzic, M., Wallace, B.M., Newman, R.F., Bradfield, G.E., & Smukler, S.M. (2019). Plant species composition and forage production-14 yr after biosolids application and grazing exclusion. *Rangeland Ecology and Management*, 72, 996-1004. https://doi.org/10.1016/j.rama.2019.07.003.

Barbour, M.G., Burk, J.H., & Pitts, W.D. (1987). Terrestrial plant ecology, 2nd. ed. The Benjamin/Cummings Publishing Company, Inc. Menlo Park, California.

COTECOCA (Comisión Técnico Consultiva para la Determinación de Coeficientes de Agostadero). (1978). Tipos de vegetación, sitios de productividad forrajera y coeficientes de agostadero para el estado de Chihuahua.

Elgarahy, A.M.,Eloffy, M.G., Priya, A.K., Yogeshwaran, V., Yang, Z., Elwakeel, K., & Lopez-Maldonado, E.A. (2024). Biosolids management and utilizations: A review. *Journal of Cleaner Production, 451*(2024) 141974. https://doi.org/10.1016/j.jclepro.2024.141974

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.

Instituto Nacional de Estadística y Geografía (INEGI). (2010). Prontuario de información geográfica municipal de los Estados Unidos Mexicanos. Chihuahua, Chihuahua. Clave 08019.

Ippolito, J.A., Barbarick, K.A., Paschke, M.W., Brobst, R.B. (2010). Infrequent composted biosolids applications affect semi-arid grassland soils and vegetation. *Journal of Environmental Management*, 91, 1123-1130. doi:10.1016/j.jenvman.2010.01.004.

Jurado, P., & Wester, D. B. (2001). Effects of biosolids on tobosagrass growth in the Chihuahuan desert. *Journal of Range Management*, 54, 89–95.

Jurado-Guerra, P., Wester, D.B., Fish, E.B. (2006). Soil nitrate nitrogen dynamics after biosolids application in a tobosagrass desert grassland. *Journal of Environmental Quality, 35*(2), 641-50. doi: 10.2134/jeq2005.0062.

Jurado, G.P., Arredondo, T., Flores, E., Olalde, V., Frías, J. (2007). Efecto de los biosólidos sobre la humedad y los nutrimentos del suelo y la producción de forraje en pastizales semiáridos. *Terra Latinoamericana*, 25, 211-218.

Jurado, G. P., Luna, M., Barretero, R., Royo, M.M., & Melgoza C.A. (2006). Producción y calidad de forraje y semilla del zacate navajita con la aplicación de biosólidos en un pastizal semiárido de Jalisco. *Técnica Pecuaria en México*, 44, 289-300.

Jurado-Guerra, P., Luna-Luna, M., Flores-Ancira, E., & Saucedo-Terán, R. (2013). Residual effects of biosolids application on forage production of semiarid grassland in Jalisco, Mexico. *Applied and Environmental Soil Science*, 2013, Article ID 835960, http://dx.doi.org/10.1155/2013/835960.

Kirk R. E. (1982). Experimental design: Procedures for the behavioral sciences. Brooks/Cole Publishing Co.

Kramer P.J. (1983). Water relations of plants. New York: Academic Press.

Lagae, H.J., Langemeier, M., Lybecker, D., & Barbarick, K. (2009). Economic value of biosolids in a semiarid agroecosystem. *Agronomy Journal, 101*(4), 933-939. doi:10.2134/agronj2008.0209x.

Lara-Villa, M.A., Flores-Flores, J.L., Alatriste-Mondragón, F., & Mata-González, R. (2022). Plant production in semiarid shrubland communities amended with biosolids in central Mexico. *Rangeland Ecology and Management*, 81, 34-43. https://doi.org/10.1016/j.rama.2021.11.004.

Mantilla, M.G., Sandoval, Y.L., Ramirez, E.M., Gasca, S.A., Navarro, F.J., Hernández, C.N., García, R.J.L., Esquivel, S.A., & Calderón, M.C. (2017). Energía limpia del agua sucia; aprovechamiento de lodos residuales. Asociación Mexicana de Empresas de Agua Y Saneamiento de México-IMTA. Cd. México. Mexico.

Martin, M., Ibarra, F., Moreno,S., Martínez, R., & Retes, R. (2019). Impacto económico de los biosólidos en la rehabilitación de praderas viejas de zacate boer en el norte de Sonora, México. *Revista Mexicana de Agronegocios*, 44, 158-168.

Martínez, F., Cuevas, G., Calvo, R., & Walter, I. (2003). Biowaste effects on soil and native plants in a semiarid ecosystem. *Journal of Environmental Quality*, 32, 472-479.

Mata-González, R., Sosebee, R. E., & Wan, C. (2002). Shoot and root biomass of desert grasses as affected by biosolids application. *Journal of Arid Environments*, 50, 477-488.

Ploughe, L.W., Akin-Fajiye, M., Gagnon, A., Gardner, W.C., Fraser, L.H. (2021). Revegetation of degraded ecosystems into grasslands using biosolids as an organic amendment: A meta-analysis. *Applied Vegetation Science*. 2021:e12558. https://doi.org/10.1111/avsc.12558.

Potisek-Talavera, M.C., Figueroa-Viramontes, U., González-Cervantes, G., Jasso-Ibarra, R., & Orona-Castillo, I. (2010). Aplicación de biosolidos alsuelo y su efecto sobre contenido de materia orgánica y nutrimentos. *Terra Latinoamericana, 28*(4): 327-333.

Ren, H., Kan, J., Yuan Z., Xu Z., A. & Han G. (2018). Responses of nutrient resorption to warming and nitrogen fertilization in contrasting wet and dry years in a desert grassland. *Plant Soil*, 432:65-73. https://www.researchgate.net/publication/327098506.

Rostagno, C. M., & Sosebee, R. E. (2001). Surface application of biosolids in the Chihuahuan desert: Effects on soil physical properties. *Arid Land Research and Management*, 15, 233-244.

Royo, M., Melgoza, A., Sierra, J. S., Carrillo, R., Jurado, P., Gutiérrez, R., & Echavarría, F. (2005). La salud de los pastizales medianos en los estados de Chihuahua y Zacatecas. II Simposio Internacional de Manejo de Pastizales. Gobierno del Estado de Zacatecas, INIFAP, Fundación Produce Zacatecas.

Salcedo-Pérez, E., Vázquez-Alarcón, A., Krishnamurth, L., Zamora-Natera, F., Hernandez-Nevarez, E., & Rodríguez-Macías, R. (2007). Evaluación de lodos residuales como abono orgánico en suelos volcánicos de uso agrícola y forestal en Jalisco, México. *Interciencia*, 32, 115-120.

SAS Institute Inc. (2011). SAS user's guide. SAS Institute.

SEMARNAT (Secretaría del Medio Ambiente y Recursos Naturales). (2002). Norma Oficial Mexicana NOM-021-SEMARNAT-2000. Especificaciones de fertilidad, salinidad y clasificación de suelos. Estudios, muestreo y análisis [en línea]. Diario Oficial de la Federación. Cd. de México. México.

SEMARNAT (Secretaría del Medio Ambiente y Recursos Naturales). (2003). Norma Oficial Mexicana NOM-004-SEMARNAT-2002. Protección ambiental-Lodos y Biosólidos-Especificaciones y límites máximos permisibles de contaminantes para su aprovechamiento y disposición final. Cd. de México. México.

SEMARNAT (Secretaría del Medio Ambiente y Recursos Naturales). (2016). Informe de la Situación del Medio Ambiente en México 2015. Compendio de Estadísticas Ambientales. Cd. de México. México.

Tilman, D. (1987). Secondary succession and the pattern of plant dominance along experimental nitrogen gradients. *Ecological Monographs, 57*(3): 189-214.

Tognetti, C., Mazzarino, M.J., & Laos, F. (2007). Cocomposting biosolids and municipal organic waste: effects of process management on stabilization and quality. *Biology and Fertility of Soils*, 43, 387-397. DOI 10.1007/s00374-006-0164-8.

Wallace, B.M., Krzic, M., Newman, R., Forge, T., Broersma, K., & Nielsen, G. (2016). Soil aggregate dynamics and plant community response after biosolids application in a semiarid grassland. *Journal of Environmental Quality*, 45:1663-1671. doi:10.2134/jeq2016.01.0030.

Wester, D. B., Sosebee, R.D., Zartman, R.E., Fish, E.B., Villalobos, J.C., Mata-González, R., Jurado, P., & Moffet, C.A. (2011). Biosolids Effects in Chihuahuan Desert Rangelands: ATen-Year Study. *Applied and Environmental Soil Science*. 2011, Article ID 717863, doi:10.1155/2011/717863.

Wilson, S.D., & Tilman, D. (1993). Plant competition and resource availability in response to disturbance and fertilization. *Ecology, 74*(2): 599-611.