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Review Article

Biosolids Effects in Chihuahuan Desert Rangelands: A Ten-Year Study

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Arid and semiarid rangelands are suitable for responsible biosolids application. Topical application is critical to avoid soil and vegetation disturbance. Surface-applied biosolids have long-lasting effects in these ecosystems. We conducted a 10-year research program investigating effects of biosolids applied at rates from 0 to 90 dry $Mg\,ha^{-1}$ on soil water infiltration; runoff and leachate water quality; soil erosion; forage production and quality; seedling establishment; plant physiological responses; nitrogen dynamics; biosolids decomposition; and grazing animal behavior and management. Biosolids increased soil water infiltration and reduced erosion. Effects on soil water quality were observed only at the highest application rates. Biosolids increased soil nitrate-nitrogen. Biosolids increased forage production and improved forage quality. Biosolids increased leaf area of grasses; photosynthetic rates were not necessarily increased by biosolids. Biosolids effects on plant establishment are expected only under moderately favorable conditions. Over an 82-mo exposure period, total organic carbon, nitrogen, and total and available phosphorus decreased and inorganic matter increased. Grazing animals spent more time grazing, ruminating, and resting in biosolids-treated areas; positive effects on average daily gain were observed during periods of higher rainfall. Our results suggest that annual biosolids application rates of up to 18 $Mg\,ha^{-1}$ are appropriate for desert rangelands.

1. Introduction

Wastewater treatment produces liquid effluent and sewage sludge. When sewage sludge is further treated for pathogen control (e.g., with anaerobic digestion or composting) the resulting product is called "biosolids." Dewatered biosolids typically have 60%–80% water content and contain a broad variety of micro- and macronutrients; about 60% of the solids content in biosolids is organic matter [1].

The US currently produces approximately 7.1 million metric tons of biosolids annually [2]. Disposal options include incineration and processing for energy recovery, landfill disposal, and land application [2]. The US EPA regulates and encourages land application both in agronomic settings and on rangelands. In fact, about 50 to 60% of annual biosolids production is used in land application [3, 4]. Land application on rangelands, especially semiarid rangelands, is particularly attractive because the climate of these ecosystems typically allows for year-around application; additionally, distance from urban areas, wide-open spaces, and large acreages in private holdings make these areas particularly suitable for land application [5]. To avoid undue disturbance of soil and vegetation, however, topical application rather than incorporation into the soil is preferred for arid and semiarid rangelands.

We conducted an extensive study of biosolids effects on Chihuahuan Desert rangelands from 1992 to 2001. Our research investigated effects of biosolids on forage production and forage quality, grass seedling emergence and early growth, plant physiological responses, quality of surface runoff and soil water leachate, soil water infiltration and erosion, biosolids decomposition, and grazing management. Our focus here is to summarize our results from a number of published and unpublished studies in a paper that will contribute to a better understanding of land application of biosolids in semiarid rangelands.

2. Study Area

Our study area was located in Chihuahuan Desert rangeland of the Trans Pecos Resource Area in Hudspeth County, Texas (USA) (mean elevation: 1350 m). The study area is located on the Sierra Blanca Ranch, about 140 km south-east of El Paso, Texas. Climate is semiarid with hot dry summers and mild winters. Precipitation averages approximately 310 mm annually, 67% of which occurs between July and October [6].

Our study area does not have a published soil survey. Our soil names are field names that are considered taxadjuncts of established soil series. Soils of the study area were dominated by three series. A Stellar loam (taxadjunct of the Stellar series) (1 to 3% slope, fine, mixed, superactive, thermic Ustic Calciargids) supports C_4 grasses (e.g., *Hilaria mutica*, *Sporobolus airoides,* and *Bouteloua gracilis*) with widely scattered shrubs (*Prosopis glandulosa* and *Ziziphus obtusifolia*). An Armesa fine sandy loam (taxadjunct of the Armesa series) (fine-loamy, carbonatic, and thermic Ustic Haplocalcid) supports vegetation dominated by *B. eriopoda*, *B. gracilis,* and scattered *Yucca elata*. A Chilicotal very fine sandy loam (taxadjunct of the Chilicotal series) (loamy-skeletal, mixed, superactive, and thermic Ustic Haplocalcids) is dominated by two shrubs, *Larrea tridentata* and *P. glandulosa* with only sparse herbaceous species.

3. Biosolids Effects on Herbaceous Biomass and Forage Quality

Commercial application of biosolids to semiarid rangelands typically occurs year round and usually involves annual applications for several consecutive years. We hypothesized that plant response to biosolids would depend on season of application as well as on the number of consecutive applications. Thus, in addition to studying rate responses to biosolids, our initial experiments included season of application and number of years of consecutive applications as factors of interest.

3.1. Methods. At the time of our work, the Texas state-regulated application rate for arid rangelands was 7 Mg ha^{-1} (on a dry weight basis). Our experimental rates were 0, 7, 18, 34, and 90 Mg ha^{-1}. Experimental plots were treated with biosolids during the dormant season (late January) or the growing season (early July, just prior to onset of seasonal rainfall). We conducted several independent experiments investigating plant response. In our longest-running experiment on plant responses [7], a total of 960 1-m^2 plots were selected in 1992 for study, half of which were centered over a *H. mutica* plant and half over an *S. airoides* plant. Baseline data were collected from each plot: herbaceous biomass was harvested after the 1992 growing season, dried, and weighed for initial standing crop. All plots were treated with biosolids in 1993; in 1994, 1995, and 1996, we retreated 720, 480 and 240 plots, respectively. Thus, one quarter of our plots received biosolids one time only (in 1993), one quarter received biosolids for two consecutive years (1994 and 1995), one quarter received biosolids three consecutive years (1993–1995), and one quarter received biosolids for four consecutive years (1993–1996). Half of our plots were provided with supplemental irrigation by applying 1.7 cm of water twice during 1993, 5 times during 1994 and 1995 and 4 times in 1996. Our intent was to elicit a response in the event of seasonal drought. Plant length was measured biweekly during the 1993 growing season to assess immediacy of plant response. We harvested peak standing crop in early October annually from 1993 to 1996 from all plots.

Other plant-response studies varied in their objectives and design, but generally, they included the above application rates and supplemental irrigation. One study investigated effects of biosolids applied twice per year for one year only on forage production as well as forage quality *H. mutica* [8]. Biosolids were applied in winter and summer or in spring and summer (1994) at 0, 7, 18, and 34 Mg ha^{-1}; plant total Kjehldahl nitrogen was measured in forage harvested for four years following biosolids application. Another study compared biosolids with commercial fertilizer applied at nutrient-equivalent rates [9]. In this study, we applied urea or monoammonium phosphate in granular form at rates calculated to supply the same amount of plant available nitrogen and/or phosphorus as biosolids applied at 0, 7, 18, and 34 Mg ha^{-1}. Production of *H. mutica and B. gracilis* was measured annually for three years.

3.2. Results. First-year responses to biosolids application coincided with above-normal rainfall and favorable growing conditions [7]. Both *H. mutica* and *S. airoides* responded almost immediately to biosolids application: increases in plant length were detected within 21 d following growing season application of 18 Mg ha^{-1}. Additionally, end-of-year plant lengths were greater in biosolids-treated plots than control plots.

Rate and season of application interacted in their effects on peak standing crop of both *H. mutica* and *S. airoides* (Figure 1). Quadratic regressions explained 94% and 98% of the variation in *H. mutica* rate response in growing season and dormant season applications, respectively. Dormant season application of 34 Mg ha^{-1} more than doubled *H. mutica* standing crop (Figure 1(a)). Biomass of *S. airoides* was not affected by growing season application of biosolids in 1993; however, dormant season application increased biomass nearly 100% (Figure 1(b)).

Effects of rate and number of consecutive years of biosolids application are illustrated in 1996 standing crop response. These factors interacted with irrigation in their effects on *H. mutica* standing crop (Figure 2). In nonirrigated plots, a quadratic regression explained from 70% to

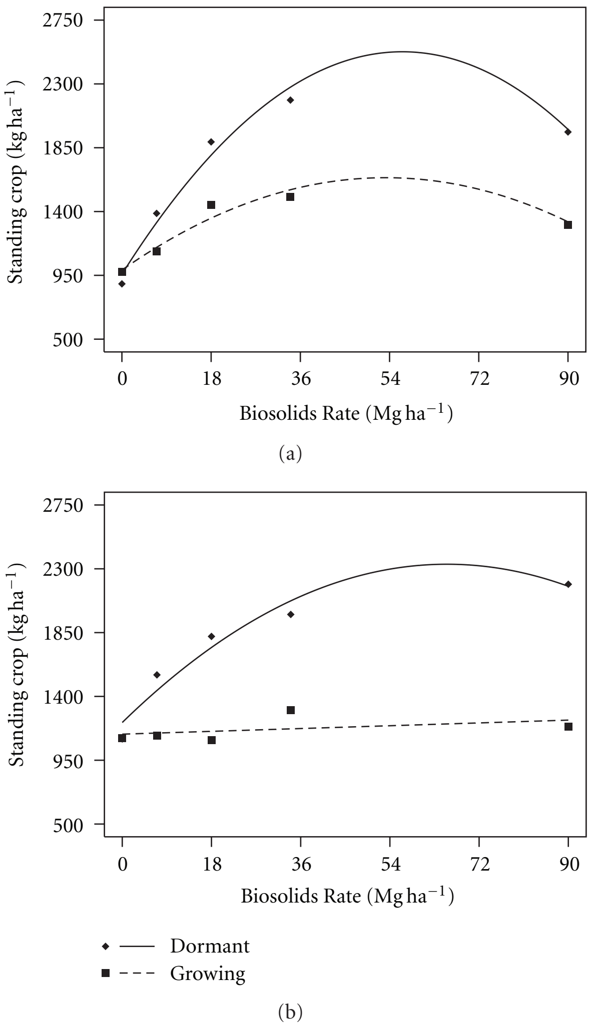

Figure 1: Standing crop (kg ha^{-1}) at the end of the 1993 growing season of (a) *Hilaria mutica* and (b) *Sporobolus airoides* as affected by season (dormant or growing) and rate of biosolids application (redrawn from [7]).

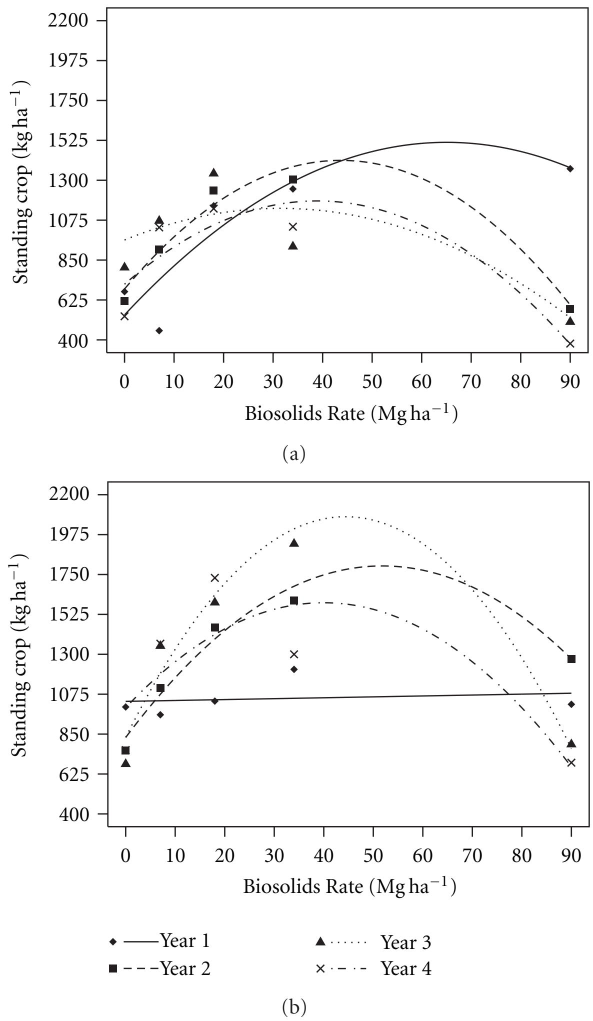

Figure 2: Standing crop (kg ha^{-1}) of *Hilaria mutica* in (a) nonirrigated plots and (b) irrigated plots at the end of the 1996 growing season as affected by one to four consecutive years of biosolids application and rate of biosolids application (redrawn from [7]).

96% of the variation in rate response (Figure 2(a)). Also, nonirrigated plots treated two, three, or four consecutive years had reduced standing crop at the highest application rate compared to plots treated only once (in 1993)—this illustrates a strong carryover effect of single biosolids applications. Biosolids application did not affect 1996 *H. mutica* production in irrigated plots that had been treated only once in 1993; however, when two or more consecutive years of biosolids were applied with supplemental irrigation, a strong quadratic rate response was shown (Figure 2(b)). We also detected an interaction between rate and number of years of application in *S. airoides* standing crop. Standing crop in 1996 increased linearly when biosolids were applied only once (in 1993). When biosolids were applied for two or more consecutive years, however, all biosolids rates increased standing crop relative to the control treatment, and the response was described with a quadratic regression. With two or three consecutive years of application, standing crop did not decrease at the 90 Mg ha^{-1} rate; with four consecutive years, however, standing crop decreased at this high rate [7].

In our forage quality study [8], we found that although *H. mutica* standing crop was affected by rate of application, this effect did not depend on year of sampling: a linear regression explained 93% of the variation in rate response. In contrast to biomass responses, the response of *H. mutica* TKN to biosolids rated depended on year of sampling (Figure 3). In general, TKN increased with increasing biosolids each year of sampling. These results suggest a strong carryover effect of biosolids applied in 1994 on both forage production and forage quality for the following four growing seasons.

4. Biosolids Effects on Plant Establishment

Biosolids provide cover to the soil surface, and the physical presence of this material can reduce soil water evaporation and moderate extremes in soil surface temperatures. Both

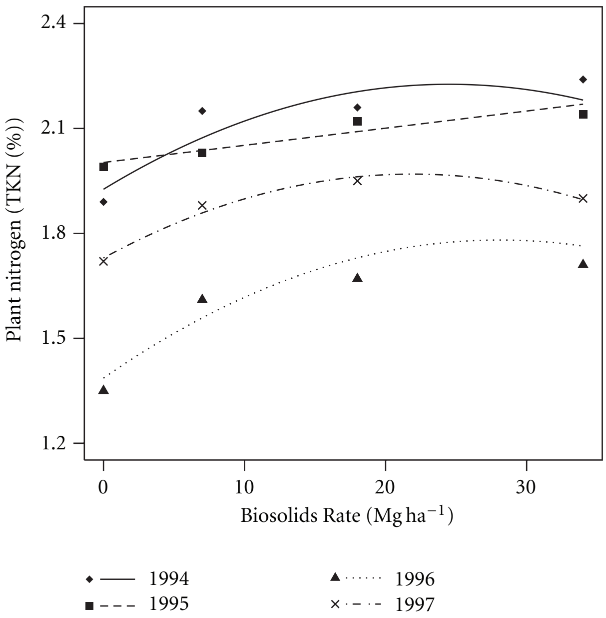

FIGURE 3: *Hilaria mutica* total nitrogen concentration (% TKN) as affected by biosolids application and years after a single application. Biosolids were applied in 1994 and forage was analyzed yearly from 1994 to 1997 (redrawn from [8]).

effects can be expected to affect seedling emergence and early seedling growth, and these effects might possibly affect long-term plant community dynamics. We conducted greenhouse and field experiments to investigate these effects on *B. gracilis* and *Leptochloa dubia*, two warm season grasses common in our study area [10].

4.1. Methods. We quantified biosolids effects on emergence and root growth in greenhouse conditions [10]. In these experiments, greenhouse pots were treated with 0 or 34 Mg ha^{-1} of biosolids; soil was air dried at the beginning of the experiment. We added 13 mm of water for seven consecutive days and monitored seedling emergence.

We also studied biosolids effects on emergence and early seedling growth under field conditions [10]. Five experiments were conducted that involved planting seeds in June, July, and August over a two-year period. Treatments were comprised of a factorial combination of two biosolids rates (0 and 34 Mg ha^{-1}) and three irrigation rates (0, 6.4, or 19 mm of water). Plots were irrigated for three consecutive days and then every other day for three irrigations; after this period, plots received only natural rainfall.

4.2. Results. In our greenhouse experiments, soil water at a 5-cm depth was higher in biosolids-treated pots on two of the first four days, also during a 10-day period after the addition of 24 mm of water for four consecutive days [10]. Although total emergence was similar in biosolids-treated and control pots by the end of the 17-day trial, seedlings of both species began to emerge in biosolids-treated pots after six consecutive days of watering at 13 mm day^{-1}; in contrast,

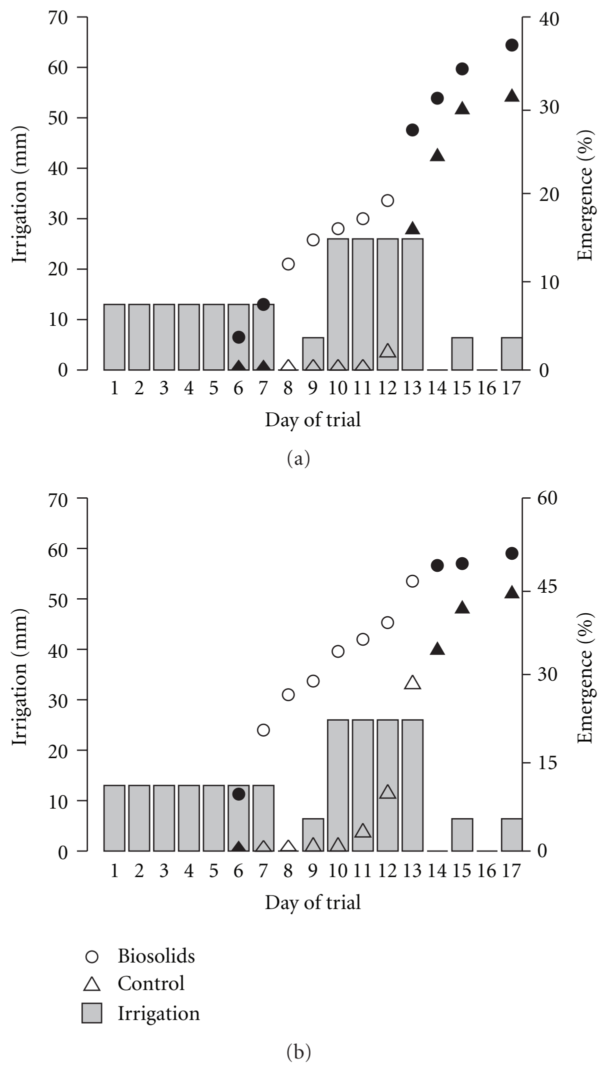

FIGURE 4: (a) *Bouteloua gracilis* and (b) *Leptochloa dubia* seedling emergence as affected by 0 or 34 Mg ha^{-1}. Treatment means for a species on a given date with open symbols are significantly different (redrawn from [10]).

emergence in control pots was delayed until irrigation was increased on day 10 of the trial (Figure 4). Biosolids had no effect on *B. gracilis* maximum root, shoot, or total plant length of 2- or 4-week old seedlings; additionally, there was no effect on total root length or root length classified by root diameter. Maximum root length, total root length, and total plant length of 4-week old *L. dubia* seedlings was greater in control pots than in biosolids-treated pots.

In our field experiments, we found that biosolids effects on emergence depended on prevailing environmental conditions, and we proposed a conceptual model (Figure 5) to explain these effects [10]. Under extremely harsh environmental conditions, biosolids are likely to have little effect on seedling emergence. Under favorable conditions, emergence can take place without the beneficial effect of biosolids. When conditions were neither harsh nor favorable; however, the presence of topically applied biosolids and the resulting

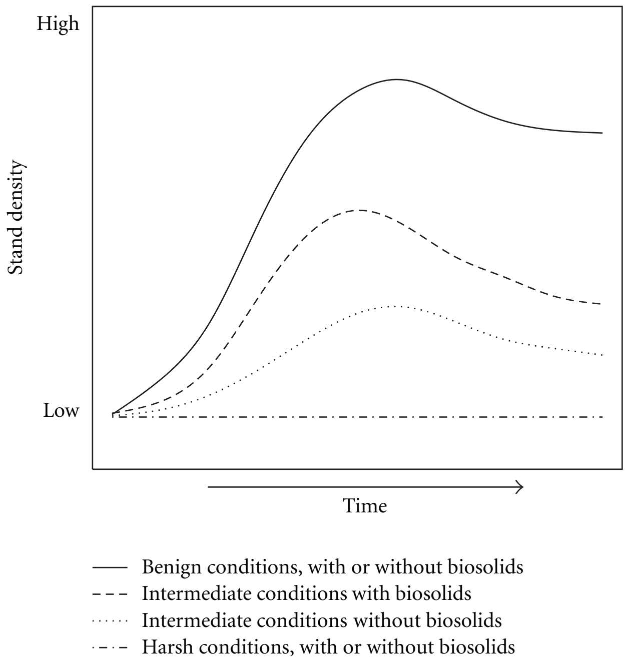

Figure 5: A conceptual model showing the effects of topically applied biosolids on plant establishment under benign, intermediate or harsh environmental conditions (redrawn from [10]).

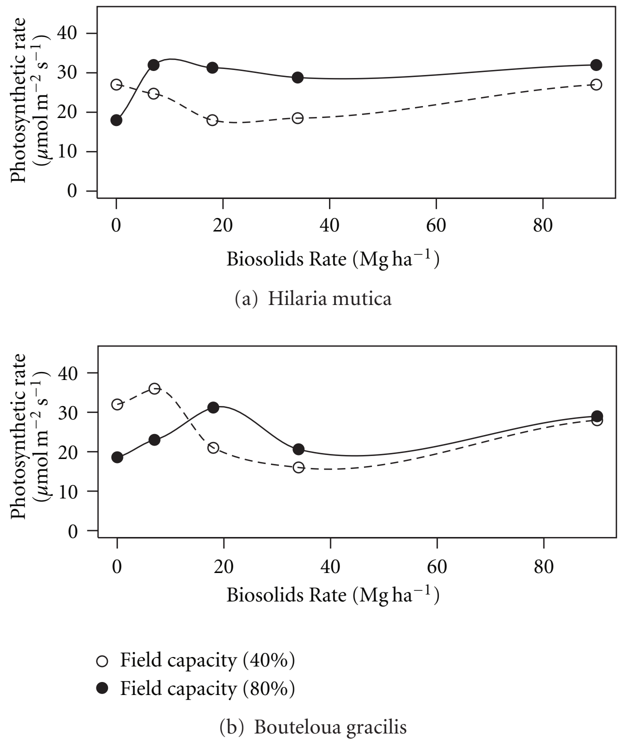

Figure 6: Photosynthetic rate (μmol m^{-2} s^{-1}) of *Bouteloua gracilis* and *Hilaria mutica* as affected by biosolids application in soil maintained at 40% or 80% field capacity (redrawn from [11]).

reduction in soil water loss and moderation of soil surface temperatures can enhance seedling emergence.

Dominguez-Caraveo et al. [19] studied biosolids effects on *B. gracilis* seedling emergence, growth, and survival under greenhouse conditions that included a watering schedule that represented below-normal amounts of water. Biosolids rates ranged from 0 to 50 Mg ha^{-1}.

In contrast to results of Hahm and Wester [10], these authors reported that both plant emergence and seedling survival decreased with increasing biosolids application. Although plant growth at 30 days was not affected by biosolids, both shoot length and aboveground biomass at 120 days increased as biosolids rates from 10 to 30 Mg ha^{-1}. They concluded that biosolids applied at 10 Mg ha^{-1} might benefit establishment of surviving plants without limiting seedling emergence or survival.

5. Biosolids Effects on Plant Physiological Responses

We studied biosolids effects on plant physiological responses of *H. mutica* and *B. gracilis* to better understand the plant production and forage quality responses of these grasses to biosolids [11]. We also studied biosolids effects on plant water relations and gas exchange of *L. tridentata,* a dominant Chihuahuan desert shrub [12].

5.1. Methods. We transplanted *H. mutica* and *B. gracilis* plants from the field into greenhouse pots and watered them through an establishment period [11]. After establishment, pots were treated with biosolids at rates of 0, 7, 18, 34, or 90 Mg ha^{-1} and held at either 40% or 80% field capacity. We evaluated photosynthetic rate, stomatal conductance, leaf area production, and foliar nitrogen concentration.

Individual *L. tridentata* shrubs were treated with 0, 7, 18, 34, or 90 Mg ha^{-1} in early February 1997 and monitored through the spring and summer [12]. We evaluated soil water responses in plots as well as photosynthesis, stomatal conductance, and predawn leaf water potential in shrubs under biosolids treatments.

5.2. Results. Biosolids affected plant physiological responses of grasses and shrubs. The leaf area of both *B. gracilis* and *H. mutica* increased with increasing rates of biosolids application [11]. This increase, however, did not always correspond to increases in photosynthetic rates (Figure 6). Plants of both species receiving the high irrigation rate (80% field capacity) increased their photosynthetic rates as biosolids application increased from 0 to 18 Mg ha^{-1}. However, as biosolids rates increased beyond 18 Mg ha^{-1}, photosynthetic rates either declined or were maintained but did not increase further in both species. Plants receiving the low irrigation rate were affected differently by biosolids application than plants receiving the high irrigation rate. The increase in biosolids rates did not produce higher photosynthetic rates in any plants under low irrigation. In addition, photosynthetic rates of both species receiving no biosolids were higher under low irrigation than under high irrigation. Photosynthetic rates were linearly related to

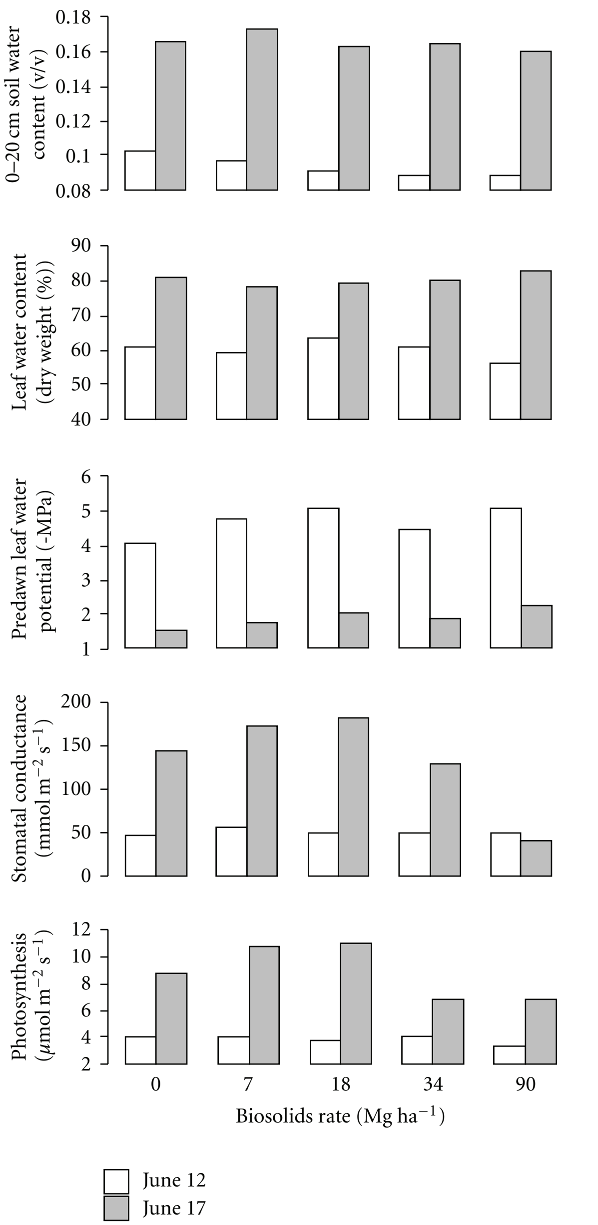

Figure 7: Photosynthesis and water relation responses on 12 June and 17 June to a 23.3 mm of rainfall that occurred 14 June 1997 in *Larrea tridentata* as affected by biosolids applications (redrawn from [12]).

stomatal conductance for both species, and there were clear trends linking plant nitrogen content derived from biosolids application to the observed responses in photosynthetic rates [11, 20].

We monitored physiological responses of *L. tridentata* to biosolids application during dry periods and for several days after precipitation events that occurred in spring and summer [12]. Our goal was to determine the physiological response of shrubs to biosolids application and changes in available water. Photosynthetic rate increased in *L. tridentata* three days after receiving a precipitation event of 23.3 mm in June. This response, however, was affected by biosolids (Figure 7). Plants receiving 7 Mg ha^{-1} and 18 Mg ha^{-1} had a marginal increase in photosynthetic rate over plants receiving no biosolids. In contrast, plants receiving 34 Mg ha^{-1} and 90 Mg ha^{-1} of biosolids had lower photosynthetic rates than plants receiving 7 Mg ha^{-1} and 18 Mg ha^{-1}.

6. Biosolids Effects on Nitrogen Dynamics

In our studies of biosolids effects on *H. mutica* and *S. airoides*, we found that season of application was an important factor in first-year responses [7]. During years of above-normal rainfall, plants began the growing season taller at the highest application rate when biosolids were applied during the previous dormant season and standing crop response to application rate was stronger when biosolids were applied during the dormant season. These results do not support common recommendations to fertilize rangelands just prior to or shortly after the onset of the rainy season (e.g., [21–23]) and pointed to a need for additional research to understand the timing of nutrient release and plant uptake.

6.1. Methods. We studied nitrogen dynamics and biosolids application with two experimental approaches. We quantified ammonia volatilization from applied biosolids with semiopen, dynamic NH_3 collectors that were placed in the field to allow for diurnal cycles of radiation, air temperature, and relative humidity [13]. We evaluated CO_2 evolution as a function of ambient temperature [24]. We also measured soil nitrate nitrogen, NO_3-N, in field plots treated with biosolids or with a nutritionally inert inorganic mulch [14]. The inorganic mulch was made of nylon and polyester fibers (3M Corporation) with a density of 0.1094 g cm^{-3}. Pieces of mulch 1.87 cm thick were cut in random shapes and applied to approximate the cover provided by biosolids (27% cover at 18 Mg ha^{-1} and 52% cover at 34 Mg ha^{-1}). The mulch was similar to biosolids in color and water holding capacity. Two experiments were designed [14]. In our first experiment, we applied biosolids in early April or early July, 1997, and sampled soil nitrogen through July 1998. In a second experiment, we applied biosolids or inert mulch in the dormant or growing season of 1998 and soil NO_3-N was measured in August, 1998.

6.2. Results. We found that volatilization losses were greater at higher temperatures than at cooler temperatures (Figure 8). Cumulative 210-h losses represented up to 16.6% of applied NH_3-N at the 7 Mg ha^{-1} rate and 12.1% at the 18 Mg ha^{-1} rate [13].

With a C : N ratio of approximately 12 : 1, biosolids might also stimulate soil microflora and thereby add soil nutrients—and this effect might be stronger with longer residence time in the system. The complexity of nutrient dynamics was illustrated by a 4-way interaction between application rate, season of application, soil depth and sampling date in their effects on soil nitrate nitrogen in our first field experiment [14]. In June 1997, surface soil NO_3^--N significantly increased at both the 18 and 34 Mg ha^{-1} rates applied in the dormant season compared to control

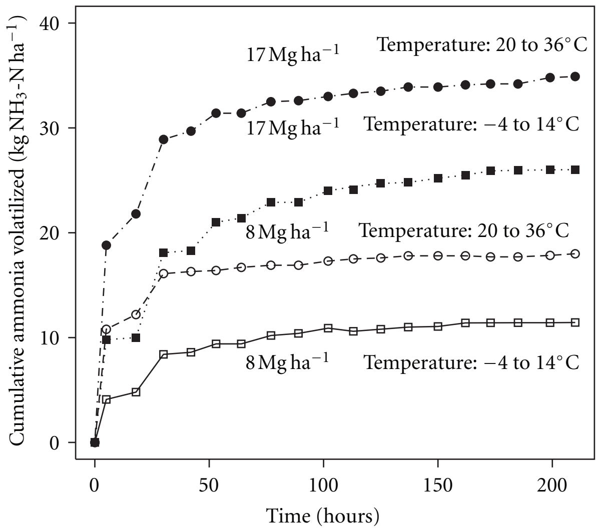

Figure 8: Cumulative ammonia volatilization loss from biosolids under hot conditions (August 1993) and cold conditions (January 1994) from plots treated with 7 or 18 Mg ha^{-1} of biosolids (adapted from [13]).

plots; subsurface soil NO_3^--N was not affected by biosolids regardless of application date. On all subsequent sampling dates (including June 1998), surface and subsurface NO_3^--N significantly increased at both biosolids rates compared to nontreated plots in both seasons of application. There was also a significantly greater effect on soil NO_3^--N when biosolids were applied in the dormant season than the growing season at both rates of application regardless of sampling depth on most sampling dates.

In the second experiment, we applied biosolids or inert mulch in the dormant or growing season of 1998 [14]. A 4-way interaction between application rate, season of application, irrigation, and sampling date affected soil NO_3^--N (Figure 9). In August 1998, under nonirrigated conditions, soil NO_3^--N was not significantly different between the control and 18 Mg ha^{-1} rates when biosolids were applied in the dormant season, and it increased significantly at the 34 Mg ha^{-1} rate (Figure 9(a)). Under irrigated conditions, biosolids significantly increased soil NO_3^--N in both seasons of application; however, a greater effect was observed with dormant than with growing season application at the 34 Mg ha^{-1} rate (Figure 9(b)). There was no rate effect with inert mulch at any season of application regardless of irrigation (Figures 9(c) and 9(d)). Biosolids increased soil NO_3^--N compared to inert mulch at both 18 and 34 Mg ha^{-1} rates in each season of application.

7. Biosolids Effects on Water Quality, Soil Water Infiltration and Soil Erosion

Application of biosolids to the soil surface of arid rangelands might have hydrological consequences. For example, topically applied biosolids might affect soil water infiltration and soil erosion. There might also be effects on soil water quality and surface runoff water quality. These effects likely will be affected by the quality of biosolids that are applied as well as the residence time of biosolids on the soil surface and the environmental conditions they experience during this residence time. We followed two experimental approaches to assess these potential effects.

7.1. Methods. We collected surface runoff water from plots treated with biosolids at rates of 0, 7, 18, 34, and 90 Mg ha^{-1} and analyzed a variety of water quality parameters [15]. In this study, surface runoff was generated using a single-nozzle portable rainfall simulator. We studied the effect of different "ages" of biosolids—that is, surface runoff was collected from plots that had been treated with biosolids 0.5, 6, 12, or 18 months prior to data collection. Differences in water quality, therefore, could have been affected not only by rate of biosolids application but also by differences in initial biosolids quality as well as the environmental conditions experienced by biosolids on the soil surface since time of application.

We also quantified quality of water that we leached through intact soil cores collected in lysimeters [16]. Cylinders (25.4 cm diameter, 1.5 m length) were inserted into Armesa fine sandy loam soils and Stellar loam soils, extracted with the soil intact, and moved to an on-site laboratory. Biosolids were applied to the surface of lysimeters at 0, 7, 18, 34 and 90 Mg ha^{-1} rates. Sufficient water was supplied to produce 1 liter of leachate which was analyzed for a broad array of constituents.

Using a portable, single-nozzle rainfall simulator, we also studied effects of surface-applied biosolids on surface water runoff, soil water infiltration, and soil erosion [17]. We simulated rainfall on bare soil as well as vegetated soil that had been treated with 0, 7, 18, 34, and 90 Mg ha^{-1}. We collected data 2.5, 5, 7.5, 10, 15, 20, 25, and 30 minutes following simulated rainfall.

7.2. Results. In our studies of biosolids effects on surface water runoff quality, we found that in general, concentrations of ammonium, nitrate nitrogen, orthophosphate, total dissolved phosphorus, copper, and manganese in runoff water increased with application rate and decreased with time since application [15]. Highest orthophosphate, PO_4^{-3}-P, concentrations were present in runoff applied at 90 Mg ha^{-1} six months prior to simulated rainfall (Figure 10). Although biosolids P contents (as analyzed in July 1996) were very similar among the four batches studied, Fe content of biosolids applied 12 months prior to rainfall simulation was almost 1% higher than in other batches, and this might have immobilized P. Orthophosphate levels were well above background levels in all treated plots—if runoff were to reach streams, eutrophication is possible. Maximum runoff NO_3^--N levels in runoff from all treatments were well below maximum recommended levels for drinking water for livestock (Figure 11). Ammonium nitrogen, NH_4^+-N, was the main form of inorganic N in runoff water. Maximum NH_4^+-N levels of 98 mg L^{-1} were measured at application rates of 90 Mg ha^{-1} in runoff from Stellar soils treated

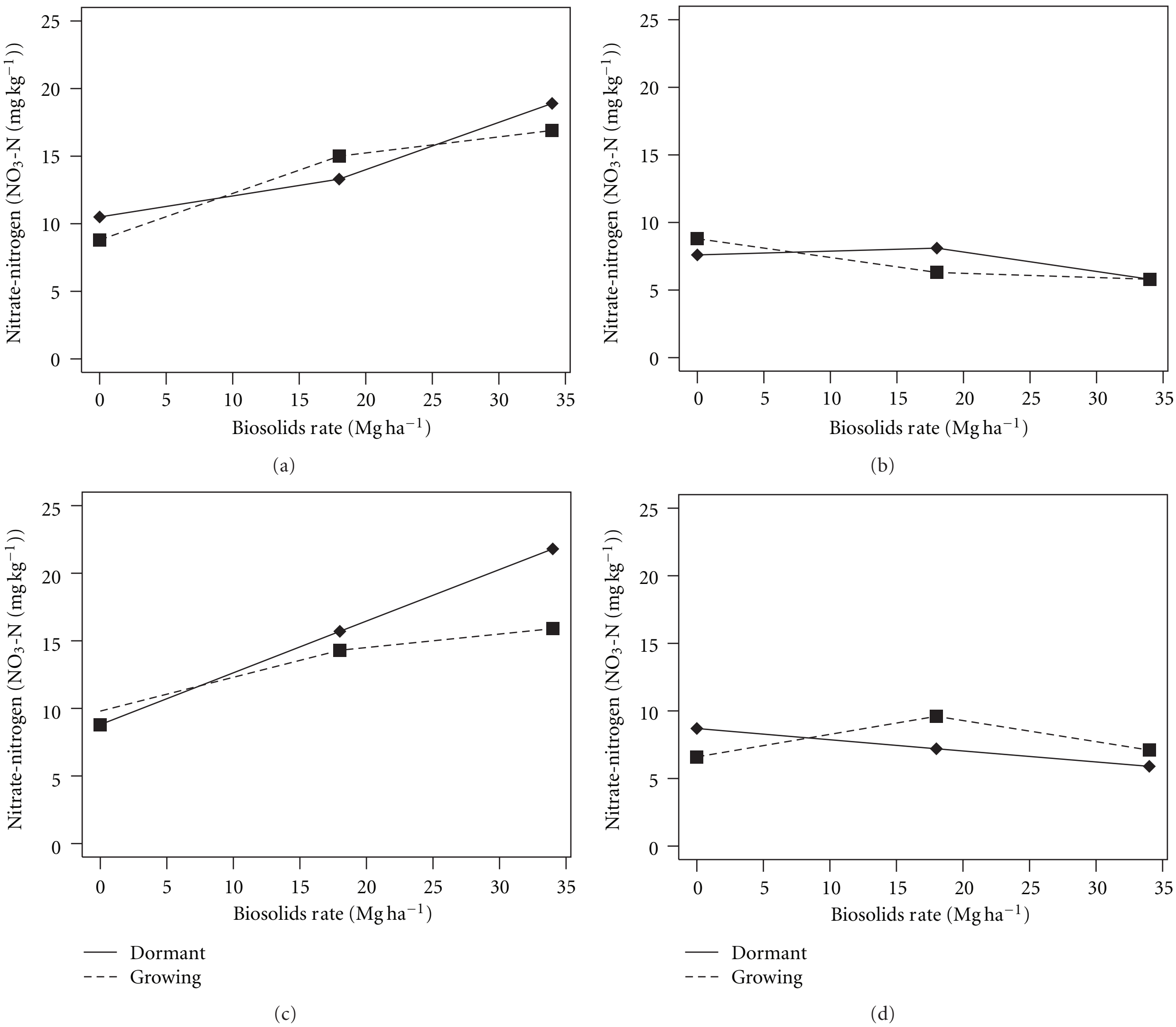

Figure 9: Soil nitrate nitrogen as affected by biosolids application, season of application, mulch type (biosolids or inert mulch), and irrigation. Biosolids were applied in 1998. (a) Nonirrigated plots treated with biosolids, (b) irrigated plots treated with biosolids; (c) nonirrigated plots treated with inert mulch, and (d) irrigated plots treated with inert mulch. Solid lines represent dormant season application; dashed lines represent growing season application (redrawn from [14]).

0.5 months before runoff collection (Figure 12). Potential NH_4^+–N losses in runoff water from biosolids-treated areas might be high, especially if rainfall occurs soon after biosolids application. Although ammonium N in runoff water was not toxic *per se*, it can affect taste of drinking water and can give rise to NH_3 under alkaline conditions which can potentially affect fish.

In our lysimeter experiment [16], we found that leachate concentration of NO_3^--N in the Armesa soil was not affected by biosolids application; however, all treatments, including the control, produced leachate with higher NO_3^--N concentrations than the maximum contaminant level (MCL) established by USEPA [25] for drinking water (10 mg L^{-1}) (Figure 13). Application of 90 Mg ha^{-1} to a Stellar soil produced higher leachate NO_3^--N concentrations (almost reaching the maximum contaminant level) than lower application rates. However, applications of 34 Mg ha^{-1} or less did not increase NO_3^--N over control levels. Orthophosphate leaching occurred mainly in the Stellar soil and was increased by biosolids application, but the levels obtained in the leachate did not represent a threat to drinking water characteristics. The concentrations of the trace elements Cd, Ba, Cr, and Be, which are regulated by USEPA, were below the MCL for drinking water regardless of biosolids treatment or soil type [16].

In our infiltration and erosion studies [17], we found that biosolids application increased soil water infiltration, and this effect was generally the most pronounced in soils where infiltration rate was initially low (Figure 14). Bare soil vulnerable to raindrop impact was crusted and had a lower steady-state infiltration rate than vegetated soil regardless of biosolids application. Application of 34 and

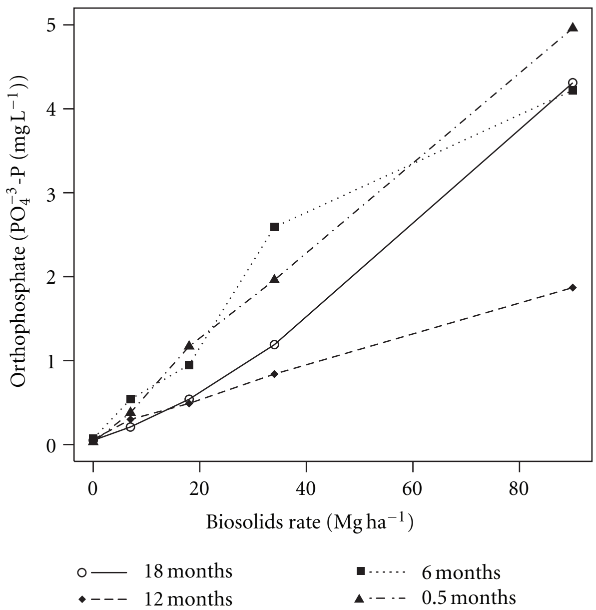

Figure 10: Orthophosphate, PO_4^{-3}-P, in runoff water from Stellar soils as affected by postapplication age (18, 12, 6, or 0.5 months) and biosolids application rate (redrawn from [15]).

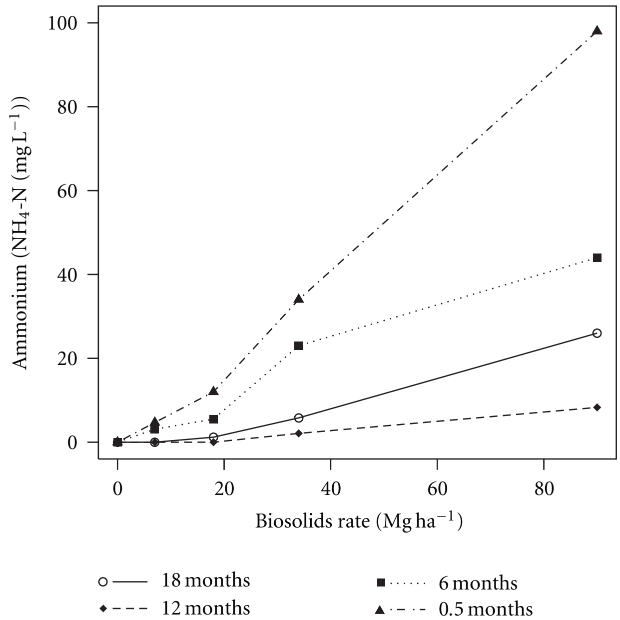

Figure 12: Ammonium, NH_4^+–N, in runoff water from Stellar soils as affected by postapplication age (18, 12, 6, or 0.5 months) and biosolids application rate (redrawn from [15]).

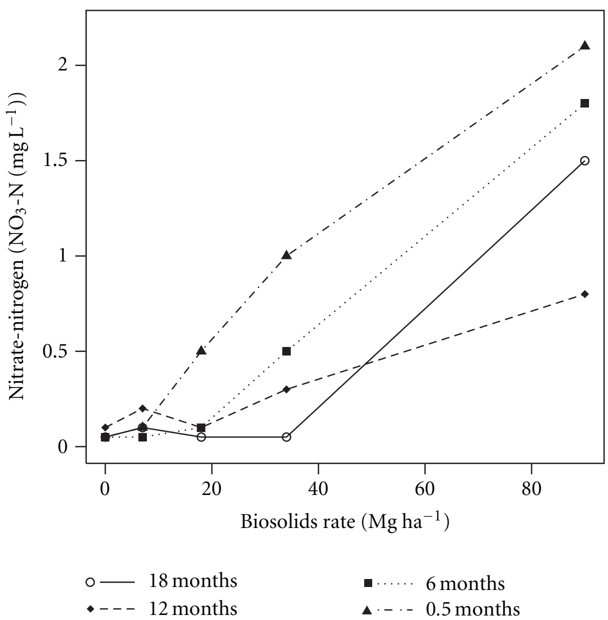

Figure 11: Nitrate nitrogen, NO_3^--N, in runoff water from Stellar soils as affected by postapplication age (18, 12, 6, or 0.5 months) and biosolids application rate (redrawn from [15]).

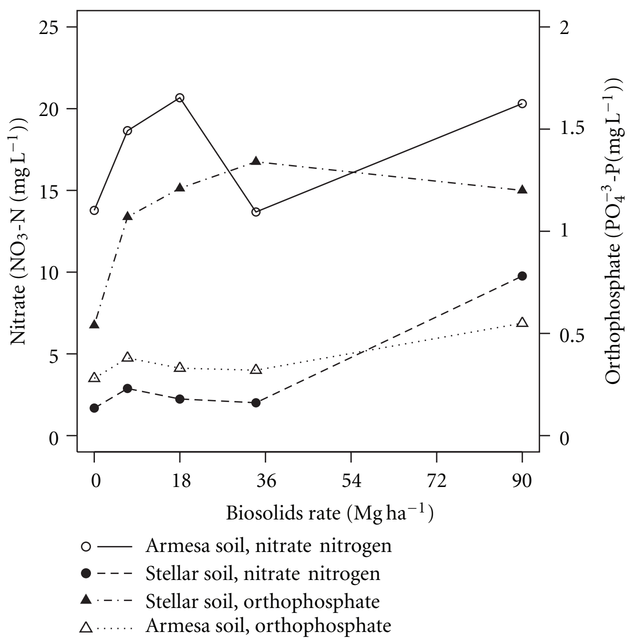

Figure 13: Orthophosphate, PO_4^{-3}-P, and nitrate nitrogen, NO_3^--N, in soil water leachate from lysimeters with either an Armesa taxadjunct soil or a Stellar taxadjunct soil treated with 0 to 90 Mg ha^{-1} (adapted from [16]).

90 Mg ha^{-1} of biosolids extended the duration of preponded and transient infiltration and elevated steady-state infiltration rate. On bare soils, application of 90 Mg ha^{-1} increased the period of transient-infiltration by about 12 min beyond that of control (non treated) plots. Cumulative infiltration was generally greater with 90 Mg ha^{-1} than all other application rates; and cumulative infiltration was greater in plots treated with 34 Mg ha^{-1} than in control plots. Infiltration in plots treated with 7 Mg ha^{-1}, however, was similar to infiltration in control plots. Biosolids also decreased soil erosion (Figure 15), and this effect was greatest when biosolids were applied to erodible Stellar soils. This

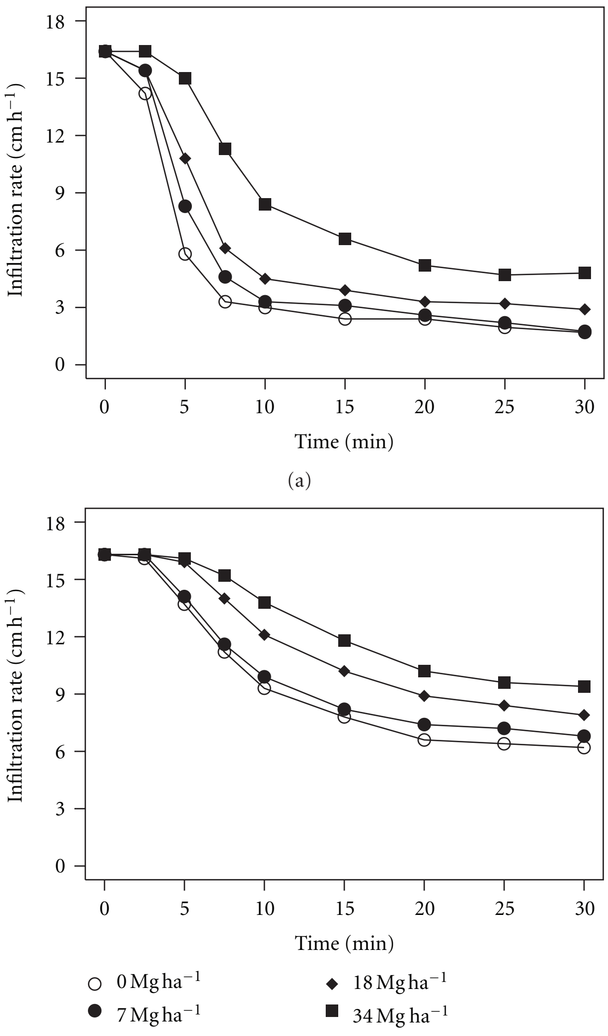

Figure 14: Infiltration rate (cm h^{-1}) during a 30-min simulated rainfall (164 mm h^{-1}) on (a) bare or (b) vegetated Stellar soils as affected by biosolids application (redrawn from [17]).

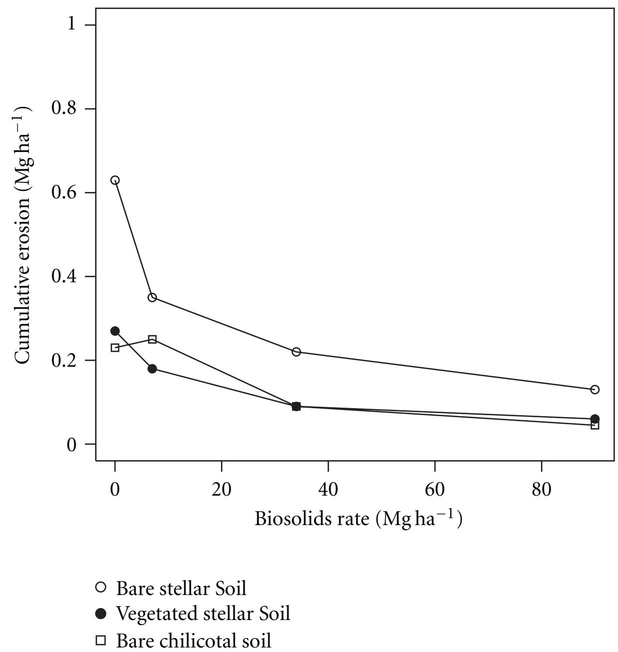

Figure 15: Cumulative erosion (Mg ha^{-1}) during a 30-min simulated rainfall (79 mm) from three soil cover conditions as affected by biosolids application (redrawn from [17]).

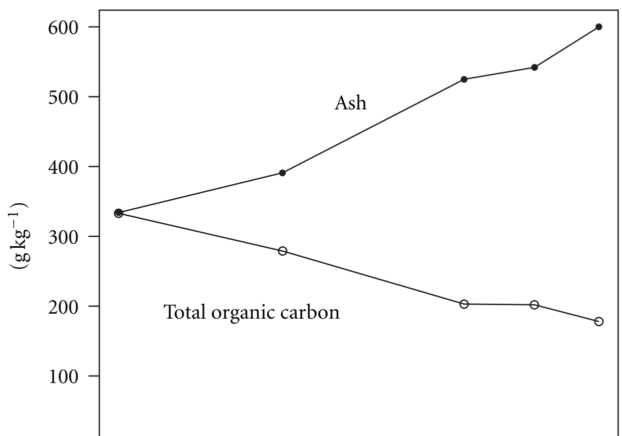

Figure 16: Ash and total organic carbon content in biosolids as affected by age of exposure on the soil surface (redrawn from [18]).

effect was likely related to the fact that biosolids lying on the soil surface increased ground cover which acted to absorb the energy of falling raindrops.

8. Biosolids Decomposition—Short-Term and Long-Term Dynamics

Because biosolids remain on the soil surface for many years following topical application on semiarid rangelands, there are both short-term and long-term decomposition considerations. We evaluated short-term carbon dynamics as affected by temperature via CO_2 evolution [24]. Relative to long-term considerations, when biosolids are incorporated into the soil during application direct analyses of biosolids decomposition are not practical and postapplication changes in biosolids decomposition must be inferred from changes in soil composition. In contrast, topically applied biosolids exist on the soil surface in semiarid environments for many years following application and can be analyzed directly for long-term composition dynamics [26].

8.1. Methods. Short-term carbon dynamics were studied with soil and biosolids in temperature-controlled chambers. Carbon dioxide samples were evaluated with an infrared CO_2 analyzer [24] in chambers at 5, 23, and 38°C. We also collected fresh biosolids and biosolids that had resided on the soil from 2 to 7 years (following single applications) and

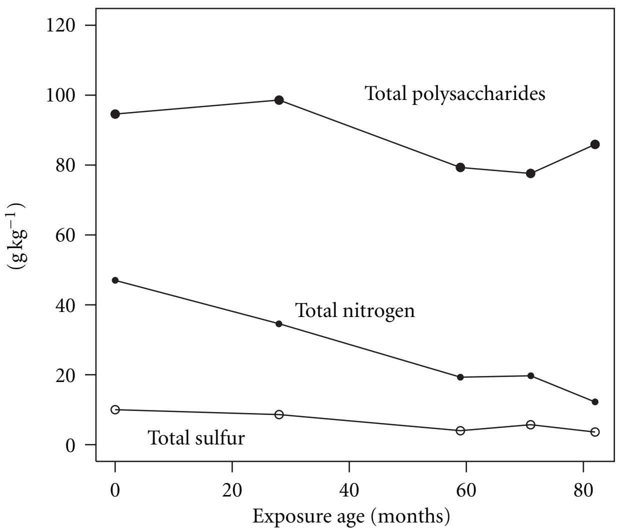

FIGURE 17: Total sulfur, nitrogen, and polysaccharide content in biosolids as affected by age of exposure on the soil surface (redrawn from [18]).

analyzed for a broad array of elements including N, P, S, Cu, Cr, Pb, Hg, and Zn [18] and talc, iron phosphates, and other minerals [26].

8.2. Results. We found that total organic carbon decreased from 340 $g\,kg^{-1}$ in fresh biosolids to 180 $g\,kg^{-1}$ in biosolids after 82 months of exposure; in turn, inorganic ash increased from 339 to 600 $g\,kg^{-1}$, corresponding to loss of organic matter and increase in inorganic material (Figure 16; [26]). Total nitrogen decreased from 50 $g\,kg^{-1}$ in fresh biosolids to 10 $g\,kg^{-1}$ in 82-month old biosolids. Decreases in total organic carbon with age exceeded decreases in total polysaccharides (Figure 17); thus, the relative content of polysaccharides in organic matter increased with age, explaining the fibrous appearance of older biosolids samples. Total and inorganic phosphorus contents decreased from 0.9 to 0.2 $g\,kg^{-1}$ with age. Successive water extractions yielded solution phosphorus consistent with dicalcium phosphate for fresh biosolids and tricalcium phosphate for biosolids for 59-month-old or older samples.

The organic matter in biosolids on the soil surface decomposed over time, with a concomitant loss in nitrogen and sulfur; loss of organic matter also concentrated inorganic materials in the residue [26]. The available phosphorus and water-soluble phosphorus decreased with exposure age—rainfall either moved phosphorus from biosolids into the soil or into surface water runoff. Even after 82 months of exposure, however, available phosphorus in biosolids was still 20 times greater than levels required for plant growth. Elemental ratios suggested that the forms of Pb, Cr, and Hg in biosolids were insoluble and immobile and that these metals have not migrated; in contrast, Zn and Cu were either leached into the soil or lost in surface water runoff.

We also evaluated the source of talc, Fe phosphates, and other minerals in the biosolids applied to our study site [26]. Talc, which was probably derived from cosmetics, was greater in the 1992–1994 biosolids than in the 1997–1999 biosolids. This diminished quantity probably reflects a lessening of its use due to health concerns. Poorly crystalline Fe phosphates were formed during the anaerobic digestion of the biosolids. Glass shards, textile fibers, and zircon grains were sand-sized components of the biosolids.

In our short-term temperature chamber study, we found that carbon loss (as quantified by CO_2) significantly increased as temperature increased from 4 h after application through day 2; after day 2, carbon loss was not significantly related to temperature [24]. Therefore, we conclude that there were no temperature limitations to biosolids applications.

9. Biosolids Effects on Livestock Performance and Grazing Behavior

The effect of biosolids on vegetation might have a carryover effect on grazing animal performance. We investigated this with a field-scale grazing experiment that used crossbred *Bos taurus* × *Bos indicus* Mexican steers [27].

9.1. Methods. A grazing trial was conducted in field plots that been commercially treated with 18 $Mg\,ha^{-1}$ of biosolids; control plots were not treated with biosolids. We studied biosolids effects on animal performance as well as grazing behavior. In our grazing behavior experiments, treated and control plots were adjacent but not separated with fencing so that animals had free-choice access cafeteria style to treated and nontreated rangeland [27].

9.2. Results. Our grazing experiments were conducted during two years (2000, 2001) of below-average rainfall [27]. Biosolids did not affect available dry matter in either year of the study. However, forage quality was improved in biosolids-treated rangeland; this effect was particularly strong for crude protein, which was increased 1% to 2% in treated areas. *In vitro* organic matter digestibility was not affected by biosolids in 2000 but was improved in 2001. Although average daily gain was generally similar between treated and control areas, biosolids had a positive effect on average daily gain during periods of higher rainfall. Grazing animals spent more time in biosolids-treated areas than in control areas grazing, ruminating, resting, and idling activities. Liver, muscle, kidney, and heart tissue analyses of grazing animals showed that biosolids did not affect concentrations of Al, Cu, Mg, Cd, Mn, Pb, or Zn.

10. Discussion and Conclusions

Topically applied biosolids have pervasive and lasting effects on desert grasslands and shrublands. We have found that biosolids reduced soil erosion and soil water runoff and increased soil water infiltration. The lowest application rate (7 $Mg\,ha^{-1}$) reduced erosion by about 40% on Stellar soils compared to bare areas not treated with biosolids. Increased soil water infiltration was associated with reduced erosion. These effects are likely explained by two factors—increased soil surface cover which reduced raindrop impact and also increased soil organic carbon (especially at the soil surface) which inhibited crust formation. These effects were seen at a square-meter level on the ground—and it is likely that they are also operating at the landscape level as well.

Water quality issues associated with biosolids application are important. In general, we found that when biosolids affected quality of water that was leached through soil that had been treated with surface-applied biosolids, these effects were observed at the highest application rate (90 $Mg\,ha^{-1}$). Our measurements showed that at application rates up to 34 $Mg\,ha^{-1}$, leachate quality was well within USEPA drinking water standards. We also found that quality of surface runoff water generally was not adversely affected by surface-applied biosolids.

Regulatory agencies base biosolids application guidelines on "plant available nitrogen" provided by biosolids relative to nitrogen needs of plants. Thus, it is important to understand how biosolids affect nitrogen dynamics. We found that cumulative 210-hour ammonia volatilization losses represented 16% of applied ammonia at 7 $Mg\,ha^{-1}$ and 12% of applied ammonia at 18 $Mg\,ha^{-1}$. Volatilization losses were also greater at higher temperatures.

Effects of biosolids on soil nitrate nitrogen were complicated by application rate, season of application, soil depth, and sampling depth. In general, we found that soil nitrate nitrogen was increased with biosolids application, and this effect was stronger when biosolids were applied in the dormant season than in the growing season. Also, soil nitrate nitrogen moved from surface (0–5 cm) to subsurface (5–15 cm) levels over time. Our comparisons of the effects of biosolids and inert mulch on soil nitrate nitrogen suggested that biosolids are responsible for the increase in nitrogen.

Biosolids also affected forage production performance and forage quality. Grasses responded to biosolids within 21 days of application. End-of-season forage production was also increased by biosolids, and this response was greater with dormant season application than growing season application in years of above-normal rainfall. Forage quality (as reflected by TKN) was also enhanced by biosolids. These effects were apparent for up to 4 years following application.

In our physiological studies we found that leaf area production in desert grasses responded positively to biosolids application which is in line with the forage production increase observed in our field studies. However, photosynthetic rates were not necessarily increased by biosolids applications. Under higher irrigation and higher biosolids rates, plants can grow a larger canopy, but a further increase in photosynthetic rates would involve higher stomatal conductance and, therefore, higher water losses. We suggest that higher photosynthetic rates were adjusted by stomatal regulation and the need of preventing excessive water loss. Also, photosynthetic rates were not only sensitive to available water but also to the nitrogen supplied by biosolids. This explains why plants treated with no biosolids and receiving high irrigation grew larger but had a low concentration of foliar nitrogen which resulted in lower photosynthetic rates. In contrast, similar plants with no biosolids but receiving low irrigation did not grow as much but maintained relatively higher levels of foliar nitrogen and higher photosynthetic rates. The effect of biosolids in desert grasses was not readily reflected in higher photosynthetic rates. But it was clear that the nutrient supply by biosolids, in combination with available water, was likely responsible for the positive effect of biosolids on plant growth.

With respect to the effect of biosolids on shrubs, biosolids application at medium rates produced a modest increase in photosynthetic rates with respect to the control, but biosolids application at high rates of 34 $Mg\,ha^{-1}$ or more decreased the photosynthetic rates. We suggest that excessively high biosolids rates might have the negative effect of intercepting precipitation and preventing plants from acquiring moisture.

Biosolids can affect long-term plant community dynamics through effects on plant recruitment. We showed that surface-applied biosolids moderated soil surface temperatures and reduced soil water evaporation. Even these ameliorative effects, however, might be insufficient to improve seedling establishment in harsh years. And these effects might be unnecessary to improve seedling emergence in years with favorable growing conditions. However, when environmental conditions are intermediate between these two extremes, biosolids can enhance early seedling growth and establishment.

The effect of biosolids on vegetation can lead to effects on grazing animals. We conducted grazing trials in two years of below-average rainfall. Although biosolids did not affect forage production, forage quality was improved compared to control areas. On average, biosolids did not affect animal gain—however, when seasonal rainfall was close to average, animals had improved performance in biosolids-treated areas. Additionally, animals spent more time grazing, ruminating, and loafing in biosolids-treated areas than in control areas. We found that forage quality was generally improved in biosolids-treated pastures compared to control pastures that were used in grazing trials. This was attributed to the nitrogen supplied by biosolids (as detected also in our greenhouse and small-plot field studies).

Based on our studies, biosolids annual application rates up to 18 $Mg\,ha^{-1}$in desert rangelands appear to be appropriate. Biosolids applications of 90 $Mg\,ha^{-1}$ represented a significant risk for negative responses in plant growth and environmental safety.

Biosolids are being produced at increasingly higher amounts in the US and the world. These materials are generally considered as waste products at their production site, but their high organic matter and nutrient contents make them a valuable resource when used in a responsible recycling program. Based on our extensive investigations of biosolids effects in Chihuahuan desert rangeland over a 10-year period, we conclude that "beneficial use application, a regulatory term of the EPA, may also be accurate in an ecological sense" [5].

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