Surface application of biosolids in the Chihuahuan Desert: Effects on soil physical properties.

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Abstract

Surface-applied biosolids, the option most used in rangelands, can improve the physical properties of degraded soils. In this study, time after biosdolids application (1-3, 6, 12, and 18 months) and application rate (0, 7, 18, 34, and 90 Mg ha^{-1}) were assessed on selected physical soil properties, from shrubland (Ustic Calciargid) and grassland (Vertic Paleargid) soils. The bulk density (BD) of the 0 to 2.5-cm soil depth was significantly ($P \leq 0.05$) decreased (approximately 10%) in the two soils; it the 90 Mg ha^{-1} treatment with respect to the 0 Mg ha^{-1} treatment. However it was not affected in the 3 to 8 cm depth. Time-to-runoff (TR) in the grassland soil and infiltration rate (IR) in the shrubland soil were significantly affected ($P \leq 0.05$) by time after biosolids application, and both, TR and IR, were significantly ($P \leq 0.05$) affected by rate of biosolids application in the two soils. For the plots treated 18 months before rainfall application in the shrubland soil, TR and IR increased from about 1.5 min and 23.7 mm hr^{-1} in the 0 Mg ha^{-1} treatment to 7 min and 104.2 mm hr^{-1} in the 90 Mg ha^{-1} treatment. Organic matter (OM) content in the 0 to 0.5- and 0.5 to 3-cm soil depth of the two soils significantly increased as rate of biosolids application increased. Neither date, nor rate of biosolids application affected the OM content of the 3-8-cm soil depth in any of the two soils. Clay dispersibility significantly ($P \leq 0.05$) decreased in soils treated with 90 Mg ha^{-1} of biosolids as compared to untreated soils. Surface applied biosolids have the

potential to improve soil physical characteristics and could be used to rehabilitate degraded rangeland soils.

Keywords: Arid soils, soil amendments, soil rehabilitation, time-to-runoff, bulk density, infiltration capacity, clay dispertion ratio, soil organic matter.

Introduction

Biosolids, a byproduct of waste water treatment plants, have long been applied to agricultural lands for adding plant macro- and micro-nutrients and organic matter to the soil. Land application has been shown to be an agronomically and environmentally acceptable means of biosolids disposal (Pierzynski et al., 1994).

Land application, which is the controlled incorporation of biosolids into the soil or spreading them on the surface, is becoming more popular as a biosolids disposal option. According to the US-EPA (1993), land application accounted for 33.3% of the biosolids used or disposed of in the USA in 1989.

Since biosolids consist mainly of organic matter, biosolids application may influence the physical properties of the soil. Physical changes associated with biosolids application to agricultural lands include an increase in soil organic matter and a decrease in soil bulk density, an enhanced water holding capacity and aggregation, and an increase in porosity and soil infiltrability (Epstein, 1975; Pagliai et al., 1981; Hall & Coker, 1983; Clapp et al., 1986; Metzger & Yaron, 1987).

In contrast to agricultural lands where biosolids are generally incorporated into the soil, biosolids are surface-applied on rangelands to avoid soil surface disturbance. A one-time surface application of biosolids on semi-arid rangelands has been shown to increase soil infiltrability and decrease soil erosion (Aguilar & Loftin, 1991 ; Moffet, 1997). However, it is not clear if the decrease in soil erosion is due to biosolids cover alone or to changes in the soil properties (i.e. changes in water dispersibility of clay). Miller and Baharrudin (1986) reported a high correlation between soil dispersibility and erosion.

Biosolids can be used as a valuable amendment for reclaiming deteriorated rangelands (Fuller, 1990). Most arid and semi-arid rangelands have been subjected to degradation processes due either to prolonged drought, past mismanagement, or the combination of both (Le Houérou, 1991). The decrease of perennial vegetation cover and biomass below a certain threshold results in a decrease in organic matter production above- and belowground. It also implies a reduction in soil organic matter and litter cover (Le Houérou, 1991). Soil crusting and a dramatic decrease in the soil infiltrability may follow these processes (Rostagno, 1989). Finally, bare areas dominate the landscape allowing runoff and erosion to prevail. This results in an increase in the spatial variability of the soil surface properties where nutrient rich islands alternate with bare areas with low potential for vegetation establishment (Schlesinger et al., 1990).

More recently, Shainberg et al. (1992) used the clay dispersion ratio (the ratio between the percent clay in undispersed and dispersed soil samples) to assess dispersibility of soils with different exchangeable sodium percentage (ESP) and its effect on soil erosion.

The objective of this study was to quantify how surface-applied biosolids affect selected physical soil properties. The variables tested for significant effect on the selected physical soil properties were i) interval between biosolids application, and ii) biosolids application rate.

The hyphotheses to be tested were: organic matter content, time to runoff, and terminal infiltration rate will not increase, and bulk density and clay dispersibility will not decrease as rate of biosolids application and time of post application increase.

Materials and Methods

Study area

The study was conducted on the Sierra Blanca Ranch, 10 Km north of Sierra Blanca in far-west Texas. The climate of the region is semi-arid and warm. The average annual precipitation is 310 mm with about 65% occurring between July and September. The mean annual temperature is 18°C (NOAA, 1994).

The physiography of the study area is typical of the northern Chihuahuan Desert: a large gently sloping to nearly level bolson, bounded by igneous hills on the west and a limestone escarpment on the north and east. Site elevation is approximately 1350 m. The bolson is drained by an ephemeral stream. Two range sites were selected for this study: a mid-section of an alluvial fan where a Chilicotal taxadjunct soil occurs (Gravelly range site), and a distal section (toeslope position) of the alluvial fan where a Stellar taxadjunct soil (Loamy range site) dominates (Allen et al., 1993). The Loamy range site is adjacent to an ephemeral stream and may eventually receive runoff from the upper land units.

The Chilicotal taxadjunct soil is classified as a fine-loamy, mixed, superactive, thermic Ustic Calciargid. This soil has a deep, well-drained pedon with an ochric epipedon, a cambic horizon, and buried argillic and calcic horizons. This soil is calcareous throughout and the calcic horizon is developed at the base of the profile (140 to 190 + cm) (Casby-Horton, 1997). The slope is 2 to 3%. Rills up to 1 m deep drain this site. Mound interspace areas are covered with a desert pavement that lays on top of a weak crust.

The Stellar taxadjunct soil is classified as a fine, mixed, superactive, thermic Vertic Paleargid. This soil has an ochric epipedon and argillic and calcic horizons (Casby-Horton, 1997). Its slope is <1%. Bare, eroded areas ranging from 1 to 10 m^2 with a thick and strong crust (Av horizon 2.5 cm) that cracks when dry are common on the Loamy range site where the Stellar soil occurs.

Vegetation of the mid-section of the alluvial fan is a shrub community dominated by creosote bush [*Larrea tridentata* (DC) Coville] and is part of the Gravelly range site (Wester & Benton, 1993). Vegetation is highly aggregated in patches generally associated with mounds 20 to 30 cm in height and 1 to 3 m diameter. Fluffgrass [*Erioneruron pulchellum* (H.B.K.) Tateoka], black grama (*Bouteloua eriopoda* Torr), and sand dropseed [*Sporobolus cryptandrus* (Torr.) Gray] are the most abundant grasses on the Gravelly range site. Ground cover characteristics of this range site were 3% basal vegetation cover, 26% gravel, 14% litter, and 3% cryptogamic cover. This site is in fair range condition. Degradation of the site has included loss of grass cover and an increase in creosotebush cover and bare ground. Evidence of soil erosion includes a dense network of rills, mounds associated with shrubs, and a desert pavement in the interspatial areas among the mounds.

Vegetation of the distal section of the alluvial fan is a grassland community dominated by tobosagrass [*Hilaria mutica* (Buckl.) Benth.] and is part of the Loamy range site. Codominant grasses are alkali sacaton (*Sporobolus airoides* Torr.) and blue grama [*Bouteloua gracilis* (H.B.H.) Lag.]. Mesquite (*Prosopis glandulosa* Torr.) and lotebush [*Ziziphus obtusifolia* (Torr. & Gray)] are widely scattered in the grassland. Ground cover characteristics of this site were 5% basal vegetation cover, 5% gravel, 6% cryptogams, 24% litter, and 60% bare ground. This site is in mid-fair range condition (Wester & Benton, 1993). Degradation processes include an increase in bare ground and an increase in the dominance of tobosagrass. Evidence of erosion includes the formation of crusted bare areas where the A horizon has been eroded.

Experimental Procedure

In January and July of 1995 and 1996, biosolids were surface applied by hand to 100 experimental units (0.50 m^2 plots) on each range site. The plots were located in bare areas. Each of these plots received only one application of biosolids. Rates of biosolids applied were equivalent to 0, 7, 18, 34, and 90 Mg ha^{-1}. Simulated rainfall was applied to 70 cm x 58 cm (0.40 m^2) plots delimited by a sheet metal frame.

Biosolids samples from the 90 Mg ha^{-1} plots were collected before and immediately after the simulated rainfall application to determine the moisture content. Soil samples from the 0 to 0.5-, and the 0.5 to 3-cm soil depth were also collected from the 12 x 70-cm strip beside the runoff plots treated with biosolids. In an area of 10 x 20-cm, either the biosolids or the gravel in the control plots were cleared and soil samples 0 to 0.5- and 0.5 to 3-cm soil depth taken with a stainless steel spatula, put in plastic bags, air-dried and kept for physical and chemical analysis. Soil samples for antecedent moisture, fraction >2mm, and bulk density determination were collected from the 0 to 2.5-cm soil depth (biosolids and surface gravel excluded) with a 5-cm diameter auger. Samples from the 3 to 8-cm soil depth were collected from the controls and the plots treated with 90 Mg ha^{-1} of biosolids, with a 5-cm diameter auger for bulk density and other physical properties determinations.

From July to October of 1996, simulated rainfall was applied with a portable single-nozzle rainfall simulator (Moffet, 1997) at a rate of 160 mm hr^{-1} and for a duration of 30 min. Runoff leaving the lower border of the plot was collected with a u-shaped collector provided with a cover to protect it from the rainfall. Runoff was collected and weighed at 5 min intervals. Infiltration was defined as the difference between total water applied during a given time period and total runoff during the same period. Since the simulated rainfall was applied to an area 1 m x 1 m, water lost by splash out of the plot area was considered to be compensated by water being splashed into the plots from outside. Time to runoff was defined as the time when measurable runoff occurred from the plot.

Organic matter of the biosolids and soil samples was determined by loss-on-ignition in a muffle furnace at 430^{o}C for 24 hours (Davies, 1974). The clay dispersion ratio (CD) was determined in samples of the 0 and 90 Mg ha^{-1} treated plots for the 0 to 0.5-, 0.5 to 3-, and 3 to 8-cm soil layers. A 50 g soil sample (< 2 mm) and 250 g DW were placed in a 500 ml plastic container and horizontally shaken for 5 min at low speed. The soil + water sample was then transferred to a 1,300 ml cylinder. The cylinder was inverted 10 times and left on the lab bench allowing the sediment to settle. The hydrometer and temperature readings were completed after 120 min. With the hydrometer reading, the undispersed clay was determined (Tan, 1996). The clay content of the dispersed sample was also determined with a hydrometer after adding 10 ml of Na hexametaphosphate and stirring the same soil sample for 5 min. The CD (%) was determined as: (undispersed clay / dispersed clay) x 100.

Statistical analysis

The experimental design for this study was a split plot arrangement of a completely randomized design (CRD). Date of biosolids application (4 dates) was the main plot factor, and rate of biosolids application (5 rates) was the subplot factor. One hundred plots were randomly located on each range site. Date of biosolids application was randomly assigned to the 20 groups of 5 plots; rate was then randomly assigned to each plot in each group. Each date x rate combination was replicated 5 times. There were 20 treatment combinations on each range site. For BD and CD only the 0 and 90 Mg ha^{-1} treatments were considered; for OM the 0, 18 and 34 Mg ha^{-1} treatment rates were considered.

Data normality was tested with Shapiro-Wilk's test (SPSS Inc., 1997). When data were not normally distributed, the Box and Cox (1960) diagnostic procedure was used to choose the most appropriate transformation. Time to runoff was transformed by Log 10.

Homoscedasticity in the main plot analysis was tested with Hartley's (1940) test. Mauchley's (1940) test was used to test for sphericity in the subplot analyses; when sphericity was not satisfied, Greenhouse-Geiser adjusted degrees of freedom were used in the F test. The data were statistically analyzed using the SPSS program (SPSS Inc., 1997). Within this program, the GLM-Repeated Measure Analysis was used to test the differences among treatments. Mean separation with the protected LSD test ($P \leq 0.05$) was used to compare variable means among treatments.

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Results and discussion

Soil Texture

Biosolids composition

Soil Bulk Density (BD)

BD, the weight of oven-dry soil per unit of volume, is an indicator of the physical condition of the soil, mainly its total porosity. In both the Chilicotal and the Stellar soils, BD of the 0 to 2.5-cm soil layer was significantly affected ($P \leq 0.05$) by rate but not by date of biosolids application. The date x rate interaction was significant ($P \leq 0.05$) in the Stellar soil at the 0 to 2.5-cm depth. In the Chilicotal soil and for the four application dates, BD was lower in the plots treated with 90 Mg ha^{-1} than in the control plots (Fig. 1). However, differences in BD were only significantly different ($P \leq 0.05$) in the Jan 95, and Jan and Jul 96 treatments. In the Stellar soil, BD was lower in the biosolids treated plots than in the control plots on 3 of the 4 application dates. However, only in Jan 95 were treatment differences significant ($P \leq 0.05$) (Fig. 1). BD of the 0 and 90 Mg ha^{-1} of biosolids, in the 3 to 8-cm soil depth in both the Stellar and Chilicotal soils were not significantly different ($P \geq 0.05$) (Fig. 1).

In the 0 to 2.5-cm layer of the Chilicotal soil, differences in BD between the 0 and 90 Mg ha^{-1} rates varied from 4.1 to 9.4%, while in the Stellar soil they varied from 4.3 to 11%. In a study where biosolids were incorporated into the soil, Wei et al. (1985) reported similar results when plots were treated with 112 Mg ha^{-1} of biosolids; differences in BD between the 0 and the 112 Mg ha^{-1} treatments were 8.3%. According to Clapp et al. (1986) for every Mg ha^{-1} of organic C added in the form of biosolids, the BD will decrease by about 0.0037 Mg m^{-3}. Olnes et al. (1998) compared this datum with those from Larson and Allmaras (1971) for naturally produced organic C and concluded that biosolids is about one-sixth as effective as organic matter from long-term grass production.

When biosolids are incorporated into the soil, a greater decrease in BD is generally obtained. Klavidko and Nelson (1979) surface-applied and disk-incorporated biosolids into the upper 5 cm of the soil at a rate of 56 Mg ha^{-1} and reported a decrease in BD after 12 months of 9.8% in the surface-applied treatment and 19.8% when biosolids were incorporated.

Incorporation of biosolids into the soil decreases the BD of the biosolids-soil mix mainly because biosolids have a lower BD than the soils. After a certain period, however, biosolids may also promote, via the activity of microorganisms, the formation and stabilization of aggregates, increasing soil porosity and further decreasing the soil BD (Metzger et al., 1987). This must be the process through which BD changes when biosolids are surface-applied as organic compounds are leached from the biosolids into the soil. The water-soluble components of biosolids are also able to bind soil constituents together, like kaolinite and montmorillonite (Metzger & Robert 1985). The fat and resin fraction of biosolids were also found to increase the soil aggregate stability (Guidi et al., 1983) which, in turn, may decrease the BD.

Time-to-Runoff (TR)

Whenever the rate of water supply to the soil surface exceeds the rate of infiltration, free water tends to accumulate over the soil surface. Only when surface storage is filled and puddles begin to overflow does runoff occur. Thus, the TR for a given rainfall is directly related to the surface storage capacity of the soil, the later stage depends on the soil surface roughness and the slope (Hillel, 1981).

The TR in the Chilicotal soil was significantly affected ($P<0.05$) by biosolids application rate, but not by date or the date x rate interaction. TR increased from slightly more than 1 min in the control plots, to more than 7 min in the plots treated with 90 Mg ha^{-1} in Jan 95. The lowest TR in the 90 Mg ha^{-1} treatment was recorded in Jul 95 (Table 1).

For a given rainfall intensity, TR increases as infiltration rate (IR) increases. In dry soils, the IR at the beginning of the rainfall is generally high, decreasing as wetting depth increases; the only driving force acting is gravity. After the surface storage has been satisfied, runoff occurs. In the biosolids treated plots, the increase in TR seems to be mainly associated with an increase in the surface roughness that reduces the velocity of runoff flow. In the plots treated with 90 Mg ha^{-1} of biosolids, a thick layer of ponded water (≈1cm) was present 5 min after the initiation of simulated rainfall. This indicates that the soil IR was below the applied simulated rainfall intensity, 160 mm hr^{-1}, soon after the rainfall started and most of the water applied was ponding. Although ponded water was also present in the control plots, the layer was much thinner.

The amount of water absorbed by the biosolids and the increase in the IR may have also accounted for the greater TR in the biosolids-treated plots. For example, the plots treated in Jan 95 with 90 Mg ha^{-1} of biosolids where the highest TR was recorded, IR was also the highest. However, the water retention capacity of the biosolids in this treatment was the lowest. This would probably indicate that the water retention capacity of the biosolids had little or no effect on TR, and the increase in TR was mainly due to the increase in IR. The plots treated in Jul 96 with 90 Mg ha^{-1} of biosolids had the lowest IR for this treatment rate and an average TR of 60 sec less (384 vs. 444 sec) than the plots treated in Jan 95. The correlation between TR and IR was $r = 0.80$, $P \leq 0.001$.

The increase in TR resulting from surface application of biosolids may be important in semi-arid rangelands where rainfall events of short duration and high intensity are common. However, a rainstorm of any considerable duration typically consists of spurts of high-intensity rain punctuated by periods of low intensity rain (Hillel, 1981). As the surface storage capacity of the biosolids-treated plots increases (amount of ponding water per unit area), consequently producing an increase in the TR, the probability of a runoff event for a given rainfall decreases. For rainfall of varying intensity, the surface storage capacity and also the soil infiltrability recovers as biosolids and soil water content tends to decrease due to internal drainage.

In the Stellar taxadjunct soil, TR was significantly affected (P<0.05) by biosolids application date and rate, although not by their interaction. The effect of date of biosolids application on TR was only significant at the 34 and 90 Mg ha^{-1} of biosolids application. At both rates, TR was higher in the Jan 95- and in the Jan 96-treated plots compared to the plots treated in Jul 95 and in Jul 96 (Table 2).

TR in the Stellar taxadjunct soil increased from an average 80 sec in the control plots to an average of 360 sec in the 90 Mg ha^{-1} treatment (Table 2). The Stellar soil had a lower IR, so a shorter TR was expected. Cracks in the Stellar soil may have subtracted some water before runoff started (a transitory surface storage capacity). Also the lower and concave slope of the Stellar soil may have counteracted the effects of the lower IR.

Infiltration Rate (IR)

The IR of the Chilicotal soil was significantly affected (P<0.05) by date and rate of biosolids application, and also by their interaction. Date of biosolids application affected IR at 34 and 90 Mg ha^{-1} and, in general, IR increased as post-application time increased. In the 90 Mg ha^{-1} treatment, IR increased from 66.6 mm hr^{-1} in the plots treated in Jul 96 to 104 mm hr^{-1} in the plots treated in Jan 95 (Table 1). In the plots treated with 34 Mg ha^{-1} of biosolids, IR in the Jul 95 treatment was lower than the IR of the plots treated in Jul 96. The biosolids applied in Jul 95 and sampled in Jul 96 before the simulated rainfall application was begun had a 6% less organic matter content than the other biosolids batches. This difference in organic matter content may explain in part the lower IR in these plots.

For each application date, IR increased as rate of biosolids application increased (Table 1). In the plots treated in Jan 95, 18 months before the rainfall application, IR increased linearly from 23.7 mm hr^{-1} in the control plots to 104 mm hr^{-1} in the plots treated with 90 Mg ha^{-1} of biosolids. For this date, and at the treatment rate of 18 Mg ha^{-1} of biosolids, IR increased by an order of two with respect to the control plots. However, to double the IR, 5-fold more biosolids had to be applied; IR increased from 50 to 104 mm hr^{-1} when the biosolids application rate increased from 18 to 90 Mg ha^{-1}. The effectiveness of the biosolids at increasing IR decreased as time from biosolids application decreased. Thus, in the plots treated in Jul 96, IR increased less than 2-fold from the control to the 90 Mg ha^{-1} treated plots.

IR in the Stellar soil was significantly affected ($P \leq 0.05$) by rate of biosolids application. Date and the date x rate interaction however, did not have a significant effect ($P \geq 0.05$) on IR. As in the Chilicotal soil, IR in the Stellar soil increased as rate of biosolids application increased. In plots treated with 90 Mg ha^{-1} of biosolids, IR was 3 times higher than in the control plots, 18.0 and 54.5 mm hr^{-1}, respectively (Table 2). Compared to the Chilicotal soil, the biosolids increased IR in the Stellar soil less effectively. In the Chilicotal soil, the plots that were treated in Jan 95 with 18 Mg ha^{-1}, IR increased 100% with respect to the IR in the control; while in the Stellar soil, 18 Mg ha^{-1} produced an increase of only 50%. This result contrasts with the results of Kladivko and Nelson (1979) who observed the maximum and most significant effect in the soil with the finest texture.

In the Stellar soil, the average IR for the control plots was less than 50% of the IR in the Chilicotal soil. The plots were placed in bare areas where the original A horizon that confers a much higher IR to this soil had been eroded away. In these areas, the soil had a hard vesicular surface horizon (Av) 2.5 to 3 cm thick, with a crust on top of it. These types of bare areas have been described in Australia where they are termed ´scalds´. According to Chartres (1992), the ´scalds´ are a form of soil crust which usually occur where the A horizon of the soil has been largely stripped by erosion, exposing either a saline or sodic B horizon". Although the area affected in the Stellar soil is not very extensive, the process and the characteristics of the soil where these ´scalds´ develop seem to be similar to those described in Australia. The Bt1 horizon of the Stellar soil has a high exchangeable Na content (12%) (Casby-Horton, 1997). This type of surface horizon has slow infiltration rates and hydraulic conductivities because it lacks macroporosity. Although the Stellar soil has deep cracks when dry, they close as the soil becomes wet. The cracks seem to have little effect on IR. Surface-applied biosolids seem to affect the structure of the soil crust very little.

The mechanism by which surface-applied biosolids increase the soil IR is not totally clear. In an experiment with surface-applied biosolids in central New Mexico, Aguilar and Loftin (1991) found that in the plots treated with 45 Mg ha^{-1} of biosolids, 99% of the simulated rainfall infiltrated into the soil in contrast to the 71 to 95% in the control plots. Biosolids had been applied 5 months before the rainfall simulation. Aguilar and Loftin (1991) considered the major factor responsible for the reduced runoff in the biosolids amended plots was the increase in surface roughness, which greatly reduced surface water flow and enhanced infiltration.

The effect of electrolyte concentration of the water applied may influence clay dispersion and further decrease the IR of the soils (Shainberg & Letey, 1984). Chemical dispersion is prevented when electrolytes are present in the soil solution. Biosolids have a high electrical conductivity when recently applied (7,000-8,000 μS cm^{-1}), and part of these soluble salts are leached into the underlying soil.

The tap water used for the simulated rainfall in this experiment had an electrical conductivity of 680 μScm^{-1}; the EC was only slightly different in the runoff from the control plots. The EC from the runoff of the biosolids treated plots however, increased substantially; the plots treated with 90 Mg ha^{-1} of biosolids on the Stellar soil in Jul 96 had an average EC of 1,280 μS cm^{-1}. Agassi et al. (1981) studied the effect of electrolyte concentration and soil sodicity on the IR of two loamy soils in Israel using simulated rainfall. Their results showed that in the non-sodic soil when a 2,300 μS cm^{-1} water was used, the IR increased to approximately 8 to 12 mm hr^{-1} as compared to a treatment with destilled water. Similarly, Oster and Schroer (1979) reported that cation concentration greatly affected IR. They observed an increase in final IR from 2 to 28 mm hr^{-1} as cation concentration in the water applied increased from 5 to 28 meq L^{-1}. The increase in TR resulting from the increase in surface roughness in biosolids treated soils, the decrease in BD and the increase in electrolyte concentration may account for the increase in IR.

Organic Matter (OM)

For the three soil layers, 0 to 0.5, 0.5 to 3, and 3 to 8 cm, OM content was higher in the Stellar than in the Chilicotal soil (Table 3 & 4). In the Chilicotal soil, OM was significantly affected ($P \leq 0.05$) by rate of biosolids application in the 0 to 0.5-cm and in the 0.5 to 3-cm layers. Date and the date x rate interaction did not significantly affect ($P \geq 0.05$) the OM content of soil in these two layers. In the upper layer, however, the effect of date of biosolids application was significant at $P=0.08$. In this layer, OM was higher in the plots treated in Jan 95 at the two biosolids application rates and in the control, as compared to the other three treatment dates (Table 3).

The effect of rate of biosolids application on the OM content in the 0 to 0.5-cm and in the 0.5 to 3-cm soil layers was significant only in the plots treated in Jan 95 and Jan 96. In the plots treated in Jan 95 with 18 Mg ha^{-1}, the OM content in the 0 to 0.5- and in the 0.5 to 3-cm soil layers was significantly ($P \leq 0.05$) higher than in the control plots. The increase in OM content of the biosolids treated plots over the OM content in the control treatment was similar for the two soil layers, 27.5 and 26.9% for the upper and lower layers, respectively. For the 34 Mg ha^{-1} treatment in Jan 95, the difference in OM content over the control was only significant in the 0.5 to 3-cm layer. For the plots treated in Jan 96 in the 0 to 0.5- and 0.5 to 3-cm layers, only the OM content of the 34 Mg ha^{-1} plots was significantly higher than that in the control plots. However, differences in OM content between the two rates of biosolids application, 18 and 34 Mg ha^{-1} were not significant ($P \geq 0.05$) at either of the soil depths on either of the two treatment dates. Soil samples were taken in a 10 x 20 cm quadrat. Although on the average, the amount of biosolids present in each of these quadrats was higher in the 34 than in the 18 Mg ha^{-1} treatments; the variation in the biosolids distribution in the quadrats was high. This may explain in part why in many cases the concentration of OM (or any compound or element assessed) was higher in the lower treatment rate.

In the Stellar soil, the rate of biosolids application had a significant effect ($P \leq 0.05$) in the OM content of the 0 to 0.5- and 0.5 to 3-cm layers. In the 0 to 0.5-cm layer of this soil, OM content increased with increasing rates of biosolids application on the four application dates, although these increments were significant ($P \leq 0.05$) only in Jan and Jul 95 (Table 4). In the Jan 95 treatment, the OM content (3.02%) was only significantly higher in the plots treated with 18 Mg ha^{-1} of biosolids than in the control (2.44%), an increase of ≈24%. On the contrary, in Jul 95, the OM content (3.54%) was only significantly higher in the plots treated with 34 Mg ha^{-1} of biosolids than in the control (2.65%), an increase of ≈34%. Differences in OM between the two treatment rates were not significantly different at either of the two dates. Similar results were reported by Moffet and Zartman (1996) who reported that organic-C increased from 0.42 to 0.53% and from 0.65 to 0.90% in the crust (0 to 0.5 cm soil layer) when biosolids were applied at 34 Mg ha^{-1} to the Chilicotal and the Stellar soils, respectively. Moffet and Zartman (1996) considered addition of dissolved organic forms in the infiltrating water and fine particles falling into the cracks the main pathways of OM incorporation into the soil.

For the 3 to 8-cm soil layer, the application of 90 Mg ha^{-1} of biosolids did not have a significant effect ($P \geq 0.05$) on the OM content of either of the two soils. Moreover, OM content was higher in the controls than in the treated plots in two (Chilicotal) and three (Stellar) out of the four application dates (Tables 4 and 5). Date of biosolids application had a significant effect on the OM content of the Chilicotal soil at the 0 and 90 Mg ha^{-1} application rates (Table 3). However, these changes seem to be related to the spatial variation in the soil OM content of the 3 to 8-cm soil layer. Thus, in the areas where plots corresponding to the treatment dates Jan and Jul 96 were located, there was a lower content of OM than the areas were the 1995 plots were located. The same differences between the 1995 and 1996 set of plots were detected in the control plots of the 0 to 0.5-cm layer, although within this layer, the differences in OM were not significantly different.

In most of the studies where biosolids were incorporated into the soil (disking, roto-tilling, etc.), soil OM, or more appropriately, the OM of the soil-biosolids mixture increased with respect to the control treatments. Since biosolids generally have a much higher OM content than the recipient soils [i.e., 31-67% (Sommers, 1977)], an increase in the OM of the soils should always occur, although the increases might not be significant. However, these increases might not occur when biosolids are surface-applied.

In surface-applied biosolids there are several possible ways by which the OM of the biosolids, or the biosolids themselves, can be incorporated into the soil: through leaching of water soluble organic compounds or by the eluviation of fine biosolids particles; as a result of the activity of the soil fauna (i.e. burrowing); and by the trampling of large animals, i.e. cows. Incorporation via the soil cracks can be an important pathway in soils where cracking occurs; i.e., in the Stellar soil.

In an study where biosolids were surface-applied at 56 Mg ha^{-1} to a silt loam soil (Aquic Hapludalf) in Indiana, Kladivko and Nelson (1979) reported that OM content in the upper 5 cm soil layer increased from 1.10 to 3.03% 2 months after the biosolids were applied. Soil samples included the biosolids crust, so the reported values correspond to the soil-biosolids mixture. When 56 Mg ha^{-1} of biosolids with $\approx$ 50% of OM and a bulk density of $\approx$ 0.50 g cc^{-1} are surface-applied, the biosolids may represent a layer of ≈ 1 cm thick. If a 0 to 5 cm soil sample is collected, 20% (v/v) or 8.1% (w/w)(bulk density of the soil was 1.29 g cm^{-3}) of this sample is accounted for by the biosolids. In any soil sample that includes the biosolids crust, the OM content would probably be approximately 4%. Differences due to leaching or decomposition may be important.

A study conducted in a New Mexico grassland where biosolids were surface-applied at rates of 0, 22.5, 45 and 90 Mg ha^{-1}, Fresquez et al. (1990) reported that OM in the 0 to 15-cm depth for the first 3 years was not significantly affected ($P \geq 0.05$) by rate of biosolids application. Four years after the biosolids were applied, however, OM for the 45 and 90 Mg ha^{-1} treatment rates was significantly higher ($P \leq 0.05$) than in the control and the 22.5 Mg ha^{-1} treatments. After 4 years, OM increased from 1.3% in the control to 1.5, 1.8, and 2.4% for the 22.5, 45, and 90 Mg ha^{-1} treatment rates, respectively. In this study, the authors did not specify if the soil sampled included the biosolids or not. However, the thick soil layer sampled may have diluted any biosolids-borne OM addition during the first years post application.

Clay Dispersibility (CD)

CD was significantly affected ($P \leq 0.05$) by rate of biosolids application in the 0 to 0.5- and 0.5 to 3-cm soil layers of the Chilicotal and Stellar soils. However, rate of biosolids application did not affect the CD in the 3 to 8-cm layer of either of the soils. For CD, the effect of treatment date was not considered.

For the two soils and for the two upper soil layers, CD decreased in the plots treated with 90 Mg ha^{-1} of biosolids relative to the control plots (Fig. 2). Biosolids application increased OM content of the two upper layers in both soils. This increase in OM might account for the decrease in the CD, a soil property inversely related to aggregate stability. In both soils, the electrical conductivity of the soil extract also increased in the biosolids treated plots. An increase in electrolyte concentration decreased CD (Shainberg & Letey, 1984). It is possible that the change in CD had more effect in the Chilicotal soil where the crust is weaker than in the Stellar soil. Well-developed surface crusts seem to be resistant to either splash or runoff erosion (Bryan & De Ploey, 1983). Voroney et al. (1981) suggested that soil erodibility decreases linearly with increasing OM over the range of 0 to 10%. The addition of organic matter via application of biosolids to soil has been found to be an effective method to increase total aggregation, and also to increase the proportion of water-stable aggregates (Clapp et al. 1986). In an incubation study using a biosolids-silt loam soil mixture lasting for 6 months, Epstein (1975) reported that the percentage of stable aggregates was greater in the biosolids-treated soil, 28 to 35%, as compared to the control soil, 17%.

In a field study, Vigerust (1983) reported that the percentage of water stable aggregates more than doubled 3 years after a single biosolids application of 50 Mg ha^{-1} to a heavy clay soil. Wei et al. (1985) also stated that aggregate stability increased as rate of biosolids application increased above a certain threshold, and reported that aggregate stability increased 3.3, 9.4, and 11.9% when biosolids were applied at 44.8,112, and 134 Mg ha^{-1}, respectively, to a silty clay loam soil. Enhancement in aggregate stability was attributed to the increase in organic matter.

Organic matter is the main factor involved in the increase of the soil aggregate stability, or what is closely related, the decrease in CD. Metzger et al. (1987) considered that both biological and chemical agents are at work in the aggregative process encountered in soil-biosolids mixtures, and that fungi make the dominant contribution to the increase in water stable aggregates following biosolids application. Accordingly, the two main binding mechanisms that might be responsible for the aggregate formation and stabilization in biosolids-amended soils are the cementation of primary particles by fungal polysaccharides and the physical entanglement of primary particles in the mesh of fungal hyphae (Metzger et al., 1987). Soil fungi population increased linearly with increasing rates of surface-applied biosolids in a semiarid grassland (Dennis & Fresquez, 1989). Large fungal populations were related to the high nutrient contents provided by the biosolids.

Water-soluble components as well as the fat and resin fractions of biosolids are also able to bind together soil constituents, increasing the water stability of soil aggregates (Guidi et al., 1983; Metzger & Robert, 1985). Water soluble components may be readily leached into the soil in surface-applied biosolids.

Conclusions

Surface applied biosolids, the disposal option most often used in rangelands, in general improved the soil physical conditions of the upper 3-cm soil layer but did not affect the 3 to 8-cm soil layer of two Chihuahuan desert soils. In the 0 to 3-cm soil layer an increase in soil OM and a decrease in BD was recorded in biosolids treated plots. Biosolids application date (1, 6, 12 and 18 months of biosolids post-application) had no effect neither on OM nor on BD. Surface applied biosolids also improved the hydrological properties of the two soils. TR and IR increased with increasing rates of biosolids application, this effect being more marked in the sandy loam (shrubland) soil than in the clay loam (grassland) soil. The effect of date of biosolids application on TR and IR was contradictory. Date of biosolids application affected the TR in the grassland soil but not in the shrubland soil, the opposite was true for the IR. Both, TR and IR seems to be mainly affected by the increase in surface roughness produced by the layer of biosolids on the soil surface. However, changes in OM, BD and electrolyte concentration in the underlying soil may also contribute to increase IR.

CD, a measure of aggregate stability and soil erodibility was affected by biosolids application in the two soils. A decrease in CD in biosolids treated soils, as well as the decrease in runoff production resulting from the increase in infiltration rate and the effect of biosolids cover may result in a decrease in soil erosion.

Thus biosolids application may improve the functioning of deteriorated ecosystems or trigger what Le Houreou (1976) referred to as the de-desertization process.

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Table 1. Time-to-runoff (TR) and terminal infiltration rate (IR) of the Chilicotal taxadjunct soil as affected by biosolids application rate and date, Sierra Blanca, Texas. TR and IR were measured between Jul 14 and October 17, 1996.

Biosolids Application Dates		JAN 95					JUL 95					JAN 96					JUL 96				
		Biosolids Application Rates (Mg ha^{-1})																			
Variable	Units	0	7	18	34	90	0	7	18	34	90	0	7	18	34	90	0	7	18	34	90
TR [a]	sec	74 a	99 ab	123 b	158 c	446 d	59 a	163 b	144 b	155 b	264 c	69 a	135 b	144 b	238 c	402 d	76 a	101 a	105 a	205 b	386 c
IR	mm hr^{-1}	23.7 aA	34.8 aA	49.9 bA	72.8 cA	104.2 dA	23.5 aA	37.2 abA	43.9 bA	47.2 bB	81.0 cB	31.0 aAB	50.2 bA	52.8 bA	71.5 cA	97.4 cAB	34.0 aB	40.0 aA	44.4 aA	63.1 bAB	66.6 bC

In a row, and for each treatment date, treatment rates with the same lowercase letters are not significantly different (P≥0.05). For the same treatment rate, dates with the same capital letters are not significantly different (P≥0.05).

[a] Date effect not significant (P≥0.05).

Table 2. Time-to-runoff (TR) and terminal infiltration rate (IR) from the Stellar taxadjunct soil as affected by biosolids application rate and date, Sierra Blanca, Texas. TR and IR were measured between Jul 14 and October 17, 1996.

Biosolids Application Dates		JAN 95					JUL 95					JAN 96					JUL 96				
		Biosolids Application Rates (Mg ha^{-1})																			
Variable	Units	0	7	18	34	90	0	7	18	34	90	0	7	18	34	90	0	7	18	34	90
TR	sec	88 aA	146 bA	159 bA	188 bAB	417 cA	99 aA	97 aA	158 bA	164 bAC	330 cBC	69 aA	128 bA	150 bA	231 cB	390 dAB	62 aA	105 abA	117 bA	135 bC	302 cC
IR[a]	mm hr-1	16.2 a	22.1 b	25.4 ab	29.9 b	50.4 c	20.4 a	30.0 ab	28.1 ab	35.1 b	52.6 c	20.3 a	23.1 a	27.7 ab	33.3 b	62.8 c	15.0 a	18.0 ab	21.1 ab	28.0 b	50.0 c

In a row, and for each treatment date, treatment rates with the same lowercase letters are not significantly different (P≥0.05). For the same treatment rate, dates with the same capital letters are not significantly different (P≥0.05).

[a] Date effect not significant (P≥0.05).

Table 3. Organic matter (OM) content in three soil layers from the Chilicotal soil as affected by biosolids application rate and date, Sierra Blanca, Texas.

Biosolids Application Dates			JAN 95				JUL 95				JAN 96				JUL 96			
			Biosolids Application Rates (Mg ha^{-1})															
Variable	Units	Soil Depth cm	0	18	34	90	0	18	34	90	0	18	34	90	0	18	34	90
OM	%	0-0.5[a]	2.40 a	3.06 b	2.71 ab		2.13 a	2.33 a	1.98 a		1.78 a	2.29 ab	2.28 b		1.96 a	2.06 a	2.15 a	
		0.5-3[a]	1.82 a	2.31 b	2.30 b		1.89 a	2.22 a	2.08 a		1.80 a	2.09 ab	2.48 b		2.01 a	2.29 a	2.07 a	
		3-8	2.53 aAB			2.18 aA	2.77 aA			2.96 aB	1.91 aB			2.03 aA	2.29 aAB			1.80 aA

In a row, and for each treatment date, treatment rates with the same lowercase letters are not significantly different (P≥0.05).
For the same treatment rate, dates with the same capital letters are not significantly different (P≥0.05).

[a] Date effect not significant (P≥0.05).

Table 4. Organic matter (OM) content in three soil layers from the Stellar soil as affected by biosolids application rate and date, Sierra Blanca, Texas.

Biosolids Application Dates			JAN 95				JUL 95				JAN 96				JUL 96			
			Biosolids Application Rates (Mg ha^{-1})															
Variable	Units	Soil Depth cm	0	18	34	90	0	18	34	90	0	18	34	90	0	18	34	90
OM	%	0-0.5[a]	2.44 a	3.02 b	2.92 ab		2.65 a	3.00 ab	3.54 b		2.59 a	2.75 a	3.06 a		2.60 a	2.80 a	2.74 a	
		0.5-3[a]	1.84 a	2.13 a	2.03 a		1.90 a	2.18 a	2.52 b		2.44 a	2.51 a	2.45 a		2.22 a	2.67 b	2.32 a	
		3-8[a]	3.25 a			3.06 a	2.22 a			2.05 a	2.25 a			2.57 a	2.57 a			2.39 a

In a row, and for each treatment date, treatment rates with the same lowercase letters are not significantly different (P≥0.05).
For the same treatment rate, dates with the same capital letters are not significantly different (P≥0.05).
[a] Date effect not significant (P≥0.05).

Table 1. Analysis of variance probability values for differences among treatments date, rate, and date x rate interactions on some physical and hydrological properties of the Chilicotal and Stellar soils, Sierra Blanca, Texas.

		Chilicotal Soil			Stellar Soil		
Variable #	Depth cm	Date	Rate	Date x Rate	Date	Rate	Date x Rate
BD#	0-2.5	0.25	0.001	0.49	0.68	0.02	0.04
	3-8	0.20	0.34	0.94	0.04	0.60	0.26
TR#		0.42	0.001	0.27	0.001	0.001	0.16
IR#		0.03	0.001	0.009	0.12	0.001	0.99
OM#	0-0.5	0.08	0.05	0.51	0.94	0.003	0.40
	0.5-3	0.97	0.001	0.15	0.59	0.01	0.14
	3-8	0.03	0.40	0.31	0.12	0.76	0.69
CD#	0.05	----	0.01	----	----	0.01	----
	0.5-3	----	0.01	----	----	0.01	----
	3-8	----	0.39	----	----	0.47	----

BD= Bulk density; TR= Time-to-runoff; IR= Infiltration rate; OM= Organic matter; CD= Clay dipersibility.

Table 2. Average biosolids chemical composition (dry matter basis) for the four application dates: fresh (sampled at the moment of application) and sampled on July of 1996 (N=5), Sierra Blanca,Texas. Mean comparisons are made, for each application date, between the variable values of the fresh biosolids and the variable values of the biosolids sampled in July 96, and among the application dates, for the variable values of the fresh biosolids.

		Biosolids Application Dates						
		Jan 95		Jul 95		Jan 96		Jul 96
		Sampling Dates						
Variable	Units	Fresh	Jul 96	Fresh	Jul 96	Fresh	Jul 96	Fresh
OM	(%)	nd	54.9	nd	50.4	nd	56.8	57.7
TKN	(g kg^{-1})	43.5 A	30.2***	35.6 B	22.8***	35.1 B	26.1***	33.6 B
P	(g kg^{-1})	16.9 A	21.4***	14.9 B	20.5***	19.4 C	19.3 (ns)	20.3 C
E C	(µS cm^{-1})	7.75 AC	2.77***	8.86 AB	2.19***	10.7 B	3.18***	6.81 C
pH		nd	6.69	nd	6.70	nd	6.51	6.33†

In a row, and for each application date, fresh and sampled on Jul 96 biosolids are either NS (P≥0.05) or *, **, and ***, significantly different at P≤ 0.05, ≤0.01, and ≤ 0.001, respectively.

In a row, fresh biosolids with the same capital letters are not significantly different (P≥0.05).

† Samples collected 45 days after biosolids application; nd = no data.

Research was supported by MERCO, Joint Venture; Texas Tech University Rangeland Improvement Line Item; and CONICET (Argentina).
We thank D. Wester, who assited with field data collection and data analysis, and E. Fish, C. Villalobos, C. Moffet, P.Jurado-Guerra, R. Mata-Gonzalez, J. Dickenson, C. Shanks, and P. Cooley who assisted with field work.
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Running head: **Biosolids effects on arid soils**.