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Persistence of Municipal Biosolids in a Chihuahuan Desert Rangeland 18 Years After Application

MOLLIE WALTON
JEFFREY E. HERRICK
ROBERT P. GIBBENS

USDA-ARS
Jornada Experimental Range
Las Cruces, New Mexico, USA

MARTA D. REMMENGA

University Statistics Center
New Mexico State University
Las Cruces, New Mexico, USA

The experimental application of municipal biosolids to degraded arid and semiarid rangelands has been practiced for many years and is becoming more common in the western United States. Previous studies have examined the effects of applying biosolids to land areas that have been degraded by one or more different factors including overgrazing, fire suppression, and increased drought frequency, duration, or intensity. However, few of these studies have measured the persistence of biosolids in the soil. This study is an attempt to recover information from an abandoned reclamation effort in which municipal biosolids were spread on a degraded rangeland on the Jornada Experimental Range in southern New Mexico. The biosolids were applied in 1979 and were still present in substantial amounts when soil samples were taken in 1997. An estimated 32% of the applied biosolids persisted as fragments greater than 2 mm in diameter for almost 20 years. There were no apparent benefits of biosolid application at this site in terms of vegetation establishment within the first four years, and there was no correlation between vegetation patterns and the concentration of biosolids remaining in the soil in 1997. It is hypothesized that much of the applied sludge remains in the soil because of the recalcitrant nature of digested biosolids combined with the environmental conditions of soil in arid systems. Long-term results from biosolid addition experiments in arid and semiarid rangelands should be considered before the practice is widely used for reclamation of degraded rangeland sites.

Keywords arid soil, decomposition, organic matter, reclamation, remediation, restoration, sewage sludge

The practice of applying municipal biosolids to arid and semiarid lands is increasing as the potential benefits of using biosolids as a soil amendment to aid in the reclamation

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Address correspondence to J. E. Herrick, USDA-ARS Jornada Experimental Range, MSC 3JER, NMSU, Box 30003, Las Cruces, NM 88003-8003, USA. E-mail: jherrick@nmsu.edu

of degraded sites are recognized. Reclamation successes from biosolid applications have been attributed to a variety of factors. These include the high level of organic carbon (C) available to soil microbes (Seaker and Soppe, 1988) and the slow release of nitrogen (N) from organic solids (Pierce et al., 1998; Seaker and Sopper, 1988). The recovery and subsequent stability of the soil ecosystem and the establishment and persistence of a healthy plant community depend on continuous accumulation and cycling of organic matter (Seaker and Sopper, 1988; Verstraete, 1986; White, Loftin, and Aguilar, 1997).

Decomposition of biosolid mixtures occurs at different rates depending on initial composition (Gilmour, Clark, and Daniel, 1996) and environmental conditions (Ajwa and Tabatabai, 1994; Boyle, 1990; McKinley and Vestal, 1985; Terry, Wilson, and Sommers, 1979). Easily degradable components include degradable carbohydrates, proteins, and soluble organic matter. These components make up the labile fraction of the biosolids. The stable fraction of biosolids can account for 30–80% of the total. This fraction includes recalcitrant components of microbial cell walls, lignin-cellulose polymers, and organic-inorganic complexes and has a much slower rate of decay than the labile fraction (Aiwa and Tabatabai, 1994; Boyle, 1990; Terry et al., 1979). Consequently, much of the organic C in biosolids is more recalcitrant than native soil organic C. It has been calculated (Anderson and Domsch, 1989; Jenkinson and Ladd, 1981), that in agricultural soils, microbial biomass C represents only 2–3% of soil organic C. Carbon stabilized in biosolids is derived from digested microbial cell walls which is more stable than lignin-derived soil organic matter (Boyle and Paul, 1989).

The recalcitrant nature of digested biosolids coupled with the environmental conditions in semiarid and arid environments may hinder decomposition of these materials on native rangelands. Decomposition rates in soil are a function of many different environmental factors. Among the most important are oxygen availability, moisture content, pH, temperature, and available minerals (Ajwa and Tabatabai, 1994). Laboratory studies conducted under optimum conditions should be considered overestimates of field decomposition rates when environmental conditions are not conducive to optimal decomposition (Gilmour and Gilmour, 1980).

Municipal biosolids have been applied to arid and semiarid areas of the southwestern United States including the Rio Puerco Watershed northwest of Albuquerque, New Mexico (Fresquez, Francis, and Dennis, 1990; White et al., 1997; Whitford et al., 1989), the Sevilleta National Wildlife Refuge in central New Mexico (Aguilar et al., 1994), the Trans Pecos Resource Area, north of Sierra Blanca, Texas (Benton and Wester, 1998), and in Eagle County in western Colorado (Pierce et al., 1998). While the benefits of biosolid amendments to forage production and plant available nutrients in arid and semiarid rangelands are evident from the literature (Aguilar et al., 1994; Benton and Wester, 1998; Fresquez et al., 1990; Pierce et al., 1998; White et al., 1997), the ultimate fate of these materials is unknown. Long-term results for biosolid application experiments are few (White et al., 1997; Witter, Giller, and McGrath, 1994). This study presents the results of a biosolid application experiment 18 years after the initial application. The longest time span of any other study in arid and semiarid regions is nine years (White et al., 1997). Terry and others (1979) suggest that the turnover time of biosolids added to soil may be on the order of hundreds of years.

This study examined the persistence of aerobically digested municipal biosolids from the Las Cruces, New Mexico, Water Treatment Plant that were applied to a small area of degraded rangeland at the Jornada Experimental Range in 1979. Soil from this area was sampled in 1997.

Site Description

The Jornada Experimental Range in southern New Mexico is located in the northern extent of the Chihuahuan Desert. Mean annual precipitation in the Jornada Basin is

FIGURE 1 Aerial photograph taken of water catchment dikes in 1998. Water catchment dikes were numbered 1–5 from right to left. Elevation gradient runs from upslope at dike number 1 to downslope at dike number 5.

247 mm (average 1915–1998), with 53% occurring between July and September when convective thunderstorms dominate. Precipitation at the study site averaged 249 mm (1979 to 1997). Mean daily maximum temperature ranges from 13°C (January) to 30°C (June). The study site is located between the basin floor and alluvial slopes of the San Andres Mountains on a Doña Ana soil (fine-loamy, mixed, thermic Typic Haplargid) with an approximately 1% slope (Tromble, 1982). A physical soil crust forms under the impact of precipitation. This crust is further stabilized by *Microcoleus vaginatus* and other cyanobacterial species (J. Belnap, personal communication). The crust increases runoff and may reduce the number of plants that can emerge even in the presence of adequate soil moisture. The study site was virtually devoid of vegetation in 1975 and was chosen to test the effectiveness of water ponding as a reclamation measure. It is believed that the severe drought of the 1950s combined with overgrazing may have been responsible for the lack of vegetative cover at this site. By 1997, when soil samples were taken, considerable recovery had occurred (Figure 1).

Materials and Methods

In 1975, five horseshoe-shaped water catchment dikes were constructed (see Figure 1). The dikes were made with an irrigation border disc pulled by a farm tractor. The dikes were constructed so that runoff water would pond to a depth of 7.5 cm during a rain event, thus increasing water infiltration into the soil and increasing the amount of soil water available to plants (Tromble, 1982, 1983). Various treatments to establish native and introduced species on the barren areas above the dikes in the years from 1975 to 1978 were unsuccessful. Municipal biosolids were applied in July of 1979 in hopes of creating a seedbed favorable for plant establishment. No artificial irrigation was applied to the site at any time.

TABLE 1 Average chemical composition of remaining biosolids recovered in 1997 by depth for all 5 catchment dikes ($n = 6$ per soil depth) compared to current (1996–1999) anaerobically digested biosolids from the Las Cruces Water Treatment Plant ($n = 19$) and the chemical composition of Sommers (1977) sludge analysis ($n = 36$) for aerobically digested biosolids (Total amounts of biosolid recovered by depth are reported at the bottom of the table.)

	Recovered soil surface		Recovered 0–2.5 cm depth		Recovered 2.5–10 cm depth		Las Cruces (1996–99)		Sommers data	
Component	mg kg^{-1}	%	mg kg^{-1}	%	mg kg^{-1}	%	mg kg^{-1}	%	mg kg^{-1}	%
Zinc	1321.33		1093.33		845.17		701.14		1800	
Phosphorus		1.77		1.3		1.03		2.58		2.7
Magnesium		0.43		0.52		0.68		0.39		0.41
Calcium		4.2		4.8		4.99		4.15		3
Manganese	337.17		277.5		332.34		247		340	
Iron	7969.67		8054.5		8166.83		83,007.7		10,000	
Copper	786.17		603.83		485.84		520		940	
Sodium		0.06		0.07		0.06		0.64		0.8
Potassium		0.32		0.43		0.58		0.34		0.4
Nitrogen		2.69		2.3		1.79		5.21		4.8
Organic matter		35.81		34.66		30.99		39.84		37.8
			kg m^{-2}		kg m^{-2}					
Biosolids			0.052		0.166					

FIGURE 2 Photograph taken July 30, 1979, of municipal biosolids application to water catchment dikes at the Jornada Experimental Range.

The municipal biosolids obtained from the Las Cruces Water Treatment Plant were aerobically digested, activated sewage sludge that was air-dried on concrete pads before being trucked to the site. The initial nutrient composition of material applied in 1979 was not available but median values for aerobically digested sludge from an average of 36 treatment plants (Sommers, 1977) are included in Table 1 for reference. Data from the anaerobic digesters currently used by Las Cruces Water Treatment Plant from 1996–1999 ($n = 19$) are also included in Table 1 for reference.

The biosolids amendment was applied to the water catchment dikes in July of 1979 (see Figure 2). One 2.7 m^3 truckload of sludge was spread behind four dikes. A fifth dike received two truckloads. Sludge was evenly spread by rake and then incorporated to a depth of less than 15 cm with a disc. This corresponds to a general application rate of 0.40 to 0.89 kg m^{-2} based on a bulk density of 500 kg m^{-3}. Application rate varied inversely with dike area. The area of each dike was calculated using ArcView software (Environmental Systems Research Institute, Inc. 1999). Due to repeated structural failure of the dikes during heavy rain events and lack of seeded plant establishment, this experiment was abandoned after 1979.

Soil Sampling and Analysis

Soils from the catchment dike area were sampled in February of 1997. Transects were laid out to perpendicularly bisect the water catchment dikes. Soil samples were taken at 0.5, 1, 2, and 5 m and at 5 m intervals thereafter on both sides of each dike ($n = 377$). The dikes and sample points were mapped using a Topcon 302D total station in radial surveying mode. The points were later downloaded to a PC to provide x and y coordinate values. At each sample point, three 0–2.5 cm soil cores and three 2.5–10 cm deep cores were collected. The soil cores for each point were composited by depth ($n = 754$).

Composited soil samples were taken to a laboratory where they were air dried and then screened with a 2-mm sieve. All biosolid aggregates 2 mm and larger in diameter were removed from each soil sample and weighed. After weighing, biosolids removed from soil samples were composited by depth. Mineral composition of the samples was quantified using standard methods by the Soil Water and Air Testing Laboratory at New Mexico State University in Las Cruces, New Mexico. Biosolid recovery was calculated based on surface area behind each dike. The Point Kriging feature of the Spatial Analyst extension of ArcView software was used to generate a spatial map based on sampled points (Environmental Systems Research Institute, Inc., 1999).

Results

Biosolid Persistence

After 18 years, an average of 32% (SE = 4.9%) of the biosolids applied were recovered as aggregates larger than 2 mm in diameter from the top 10 cm of soil to which they were applied. Most of this material was recovered from below the soil surface; few biosolid aggregates were still apparent on the soil surface in 1997. Surface biosolids were only encountered in 5 of the 377 sample points shown in Figure 3 and accounted for less than 1% of the material recovered. Biosolid concentration in the soil was highly variable, both within and among dikes (Figure 3). Correlation analysis showed a strong linear relationship (Pearson's correlation = 0.85) between amount applied and amount recovered from behind each dike (Figure 4). A large portion of the original application of biosolids remained over the entire area regardless of the dike in which it was applied. There was no correlation between vegetative cover and biosolid recovery (Pearson's correlation = −0.08).

Biosolid Characteristics

Biosolid aggregates recovered from the site in 1997 were stable when submerged in water and remained intact even in a 0.5% solution of sodium hexametaphosphate (a dispersing agent). Ash accounted for 66% of the material remaining in the soil. Calcium, nitrogen, iron, and phosphorus were the primary constituents of the ash (Table 1). Calcium, nitrogen, iron, and phosphorus also represent the top four mineral constituents of sludge now produced by the anaerobic digesters currently used by the city of Las Cruces (Table 1). Mineral concentrations were similar in the biosolids collected from the two soil depths and at the soil surface (Table 1). The C : N ratio for the aerobically digested biosolids in Sommers (1977) is 6 : 1, while the C : N ratio for the 18-year-old Las Cruces sludge is 8 : 1.

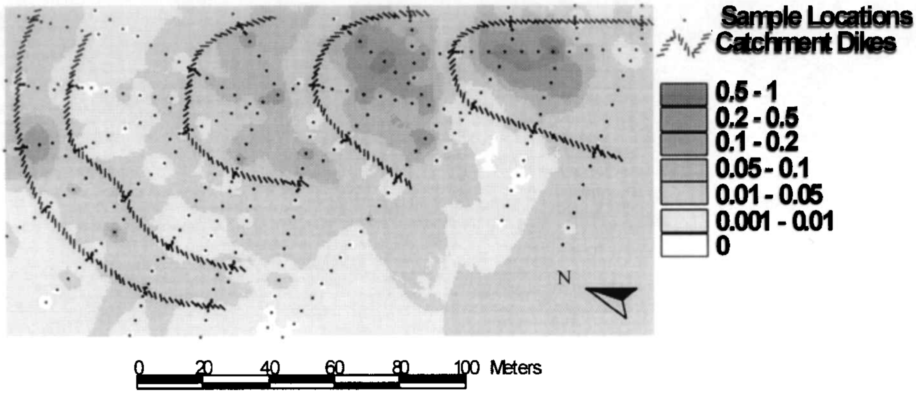

FIGURE 3 Estimated amount of remaining biosolids (kg m^{-2}).

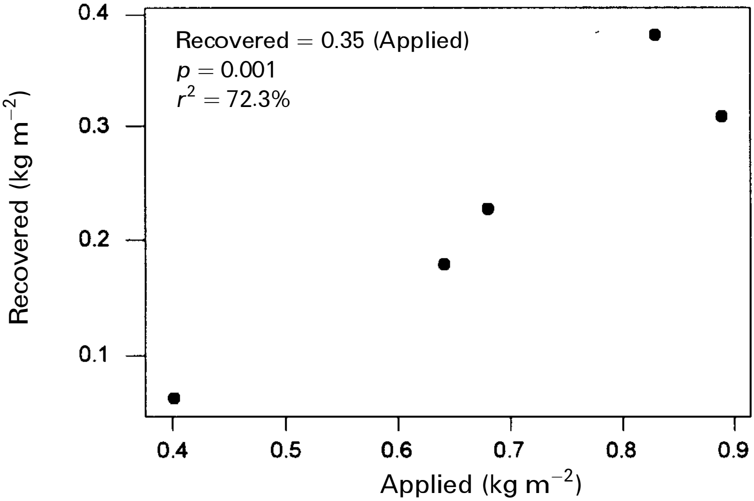

FIGURE 4 Relationship between mass of biosolid applied and recovered for each of the five dikes. Regression based on a zero intercept.

Discussion

Minimum Estimate of Biosolid Persistence

The persistence of biosolids for 18 years after a single application was not anticipated. The entire area has an average of 32% of the initial biosolid amount remaining. This estimate is conservative as only large (>2 mm) aggregates were recovered from the soil, sampling was limited to the surface 10 cm, and no attempt was made to quantify material which was redistributed outside the area to which it was applied. Smaller aggregates were visible in soil samples and could represent a substantial additional amount of material that was not recovered. Biosolid amounts were higher in the 2.5 to 10 cm soil cores than in the 0–2.5 cm cores (Table 1). Although no material was observed at greater depths, it is possible that some biosolid was mechanically incorporated more than 10 cm deep and biological processes may have taken it even deeper.

Incorporation of the biosolids into the soil would have destroyed soil surface crusts and exposed the area to erosion. There is a high level of overland flow across these landscapes. It is known that the dikes were breached during storm events. These events could have carried some material off site. Wind erosion could also have resulted in loss of material from the site. The soils at the site are highly erodible when not stabilized by microbiotic crusts. The only biosolid material left at the surface in 1997 was in depressions where it was protected from redistribution by wind.

Vegetation establishment and biosolid decomposition show no correlation with each other (Pearson's = −0.08). The lack of a positive correlation supports the assumption that the material remaining in the soil has little effect on plant growth under these conditions. The lack of a negative or positive correlation indicates that vegetation establishment and subsequent changes in the soil environment did not appear to affect the decomposition rate.

Comparisons with published data on typical ash content of aerobically digested sludge indicate that decomposition of the biosolids at this site is occurring slowly (Table 1; Sommers, 1977). Digested biosolids have a low C:N ratio (usually less than 10) (Gilmour, Clark, and Sigua, 1985; Lerch et al., 1992; Qiao and Ho, 1997;

Terry et al., 1979). The small amount of readily digestible organic carbon makes digested biosolids unsuitable for rapid decomposition (Ajwa and Tabatabai, 1994; Qiao and Ho, 1997; Spinosa, Mininni, and Brunetti, 1987). The assumed increase in the C:N ratio of recovered material (8:1) relative to that reported for initial composition (6:1) by Sommers (1977) suggests that carbon in biosolids is relatively resistant to decomposition in this environment. It is also possible that some N mineralization occurred.

The substantial amount of biosolids remaining in this area is attributed to the nature of the initial biosolids' composition. The biosolids were aerobically digested prior to application; therefore the nutrients in the sludge were primarily those retained within the microbial cell walls. Many readily available nutrients are assumed to have been removed or immobilized in the digestion process.

Environmental Conditions

For decomposition to occur, a suite of environmental conditions must be met. Moisture, pH, temperature, O_2 level, and initial biosolid substrate content all factor into the decomposition rate (Ajwa and Tabatabai, 1994; Boyle, 1990; McKinley and Vestal, 1985; Terry et al., 1979). Lab studies generally overestimate field decomposition rates because they are usually conducted under optimum conditions (Gilmour and Gilmour, 1980). Moisture content of the soil and of the sludge itself is also important for decomposition (Boyle, 1990; McKinley and Vestal, 1985; Spinosa et al., 1987). Moisture and temperature have to be within optimal ranges at the same time in order for rapid decomposition to occur (Ajwa and Tabatabai, 1994).

Comparable semiarid rangeland biosolid studies were completed under somewhat different environmental conditions, including temperature and timing and amount of precipitation (Whitford et al., 1989; Aguilar et al., 1994; Fresquez et al., 1990; Pierce et al., 1998; Benton and Wester, 1998). Unfortunately, none of these reports include decomposition rate estimates.

Although biosolid application studies in arid and semiarid lands do not report decomposition rates, most address the effect of the biosolid treatment on the plant community (Aguilar et al., 1994; Benton and Wester, 1998; Fresquez et al., 1990; Pierce et al., 1998). In contrast to the Jornada study in which there was little evidence of short-term, direct effects on plant establishment, most of these studies found that biosolid application had a positive impact on plant community composition or production. For example, in the Upper Rio Puerco Watershed, Fresquez and others (1990) report a change in the plant community structure following biosolid application. At application rates of 2.25 to 4.5 kg m^{-2}, there were reported decreases in total plant density, species richness and plant species diversity measured over a four-year period. However, the net result of biosolid addition was favorable for the plant community as blue grama (*Bouteloua gracilis* Lag. ex Steud.), an important perennial forage grass, increased in aboveground biomass and density in relation to broom snakeweed (*Gutierrezia sarothrae* Britton & Rusby), an invasive, unpalatable plant. The increase in available nutrients, primarily nitrogen, as a result of the biosolid application was used to explain the shift in the plant community. Pierce and colleagues (1998) report an increase in aboveground biomass of perennial forage grasses at application rates of 1.0 to 2.5 kg m^{-2} two years following biosolid application, but in a year with higher than average precipitation. At the Sevilleta National Wildlife Refuge, there was no significant difference in aboveground biomass and vegetative cover following 2.0 or 4.5 kg m^{-2} biosolid addition, except when there was a period of adequate precipitation (Aguilar et al., 1994). Benton and Wester (1998) report that biosolid application in the dormant season has a positive effect on plant growth.

In the Rio Puerco Watershed in west-central New Mexico, Whitford and others (1989) reported no measurable beneficial effects on net production and activity of soil biota after applying 0.1 kg m^{-2} of municipal biosolids to rangeland plots. White and colleagues (1997) documented chemical changes in the soil over an 8-year period following the application of 2.25, 4.5 and 9.0 kg m^{-2} of biosolids to research plots. At this site, biosolids were not incorporated into the soil and any visible biosolids were physically removed before sampling the soil. Results show that nearly all of the soil chemical properties were approaching values of the untreated soil after eight years. However, nitrogen mineralization rates remained significantly higher in the two higher application treatments nine years after application.

Based on a review of these studies, it is hypothesized that the apparent lack of significant plant establishment at this site in the first four years after application may be due to a lack of appropriate weather conditions. Plant establishment in this ecosystem is episodic and relatively rare, as illustrated by relatively low success rates in seeding trials reported by Ethridge and others (1997). It is further hypothesized that the lack of a correlation between subsequent perennial plant establishment (as indicated by current patterns) and biosolid concentration in the soil may be due to the fact that by the time establishment occurred, most of the readily available nutrients probably already had been lost.

At the Jornada Experimental Range, the rainy season occurs in the summer months. Although there may be adequate moisture at this time, soil temperatures can be much higher than the optimum range for decomposition (mean daily maximum is 30°C in June). Microbial systems generally cannot operate when temperatures rise above a certain range (35–45°C) (McKinley and Vestal, 1985). At other times of the year, temperature may be in the optimum range, but moisture is limiting.

In other studies where irrigation was applied to biosolid amendment treatments in semiarid grasslands, biosolids did not persist as visible, stable aggregates (McCaslin, personal communication based on study published in McCaslin et al., 1987; Whitford, personal communication based on study published in Whitford et al., 1989).

Conclusions

Much of what is known about decomposition rates and the effects of biosolid amendments is based on laboratory studies. Many of the existing field studies were completed under different environmental conditions, including mine spoils and mesic agricultural systems. Field studies in arid and semiarid rangeland ecosystems all lasted less than 10 years, and most were less than 5 years in duration. Information obtained from these studies is useful, but cannot be interpreted to mean that land application of biosolids will have positive effects on all arid and semiarid ecosystems.

If biosolids are to be extensively applied to western rangelands, there is a need for data from long-term studies on biosolid decomposition in arid and semiarid lands under natural conditions. Results from this study indicate that significant quantities of biosolids may persist for over 15 years in these environments. Long-term studies conducted under natural conditions need to be considered before undertaking large-scale application of municipal biosolids to semiarid and arid rangelands, particularly if repeated applications are to be made.

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