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Soil and runoff response to dairy manure application on New Mexico rangeland

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ABSTRACT

Manure disposal is a major challenge for the fast-growing dairy industry in New Mexico. There are currently over 355,000 milking cows in the state and limited cropland on which to use the manure generated by these cows. On the other hand, 80% of the state lands classified as rangelands are suffering from a lack of organic matter and nutrients. Application of dairy manure to rangelands could serve a dual purpose: (1) manure disposal from dairies and (2) soil amendment to improve soil characteristics and promote herbaceous production. Manure was applied at two rates according to phosphorus (P) content: (1) a recommended (light) rate (54 kg P ha^{-1}) to enhance blue grama growth and (2) a gross over-application (heavy) rate (493 kg P ha^{-1}) to determine the effects on runoff and soil properties. Light applications enhanced soil properties including decreased sediment runoff, increased soil organic matter, increased extractable P, and increased soil moisture, whereas heavy applications increased soil salinity, sodium adsorption ratio, and runoff water. Dairy manure can be safely applied at light rates to conserve and enhance rangeland soil properties and their herbaceous productivity. Manure disposal at heavy rates are unsafe. Further study is required to find out if other safe disposal exists between the light and heavy treatments.

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1. Introduction

The dairy industry has emerged as an economic engine in New Mexico in recent years with the 7th largest dairy industry of the U.S. and this trend of expansion is expected to continue (Cabrera and Hagevoort, 2007). Milk production has more than doubled from 1.63 billion kg in 1995 to 3.45 billion kg in 2006. Currently, dairying is the largest agricultural industry in New Mexico, contributing 40% of the agricultural cash receipts with more than 355,000 milking cows, which are growing in number at a rate of 5% annually (Cabrera and Hagevoort, 2007). Milk production and its related industries are instrumental in the economic growth of New Mexico.

However, dairy farming brings not only economic development, but also introduces environmental challenges including manure disposal. A lactating cow might produce 68 kg of wet manure a day (ASABE, 2005). With 2080 lactating cows per farm (Cabrera and Hagevoort, 2007), many dairies in New Mexico might not have enough cropland to use all the manure cows produce (Cabrera et al., 2008). This problem is expected to worsen as the industry continues to grow.

The manure excreted by dairy cattle could be recycled as fertilizer to rangelands. Manure amendments can help maintain or improve fertility on rangeland soils, but they could also help to reverse soil degradation in New Mexico and across the southwestern U.S. (Obi and Ebo, 1995). In addition, the best alternative to decrease nutrient leaching and runoff that takes place during intense season-specific rainfalls is through addition of organic material to fragile soils (Obi and Ebo, 1995). Application of organic matter may also provide other environmental benefits such as decreased erosion, improved forage and habitat for wildlife, improved soil fertility, and improved watershed function (Stavast et al., 2005). Manure can act as a biofertilizer that enhances herbaceous production (Abdel Magid et al., 1995; Mata-Gonzalez et al., 2002).

Low nutrient rangeland soils induces low vegetation productivity, which further reduces organic matter and nutrient cycling. However, dairy manure application at a rate of 54 kg ha^{-1} of P has been shown to improve herbaceous crop cover in robust blue grama grass (*Bouteloua gracilis* (H.B.K.) Lag. Ex Steud.) growth characteristics such as greater inflorescence height and density (Stavast et al., 2005), which might suggest light disposal of dairy

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manure to rangeland increases plant productivity. This would imply some effect on soil organic matter (SOM) content and nutrient availability, but the relationship on blue grama rangeland remains to be tested.

The application of dairy manure would help alleviate manure use problems for dairies and provide benefits to rangelands, but it also has potential problems. Dairy manure can become non-point source pollution because manure particles can be lost in runoff events during intense storms (Wang et al., 1996). Runoff of manure P in particular could lead to contamination of water supplies resulting in nutrient enrichment and consequent eutrophication (Carpenter et al., 1998; Sharpley et al., 1994). Eutrophication has been recognized as the main cause of impaired surface water quality in the U.S. (US-EPA, 1996). Another potential concern from manure application is the salinization of both runoff water and soil (Pratt, 1979). Because the water in urine and fresh manure evaporates, high salt concentrations remain after drying (Van Horn et al., 1994). In addition, dairy manure may also contain salts from spilled mineral supplements or residue from salt licks placed in the dairy lots (Van Horn et al., 1994).

Whereas dairy producers are facing manure use challenges, resource managers and ranchers in New Mexico are striving to reach full production potential of rangelands. New Mexico's rangeland soils have been degraded by numerous circumstances including over-grazing, drought, and off-road vehicle use (Wood et al., 1986). Many of rangeland soils have lost fertility and quality through erosion, which carries away nutrients and soil particles (Stavast et al., 2005). Eroded soils provide less favorable hydrologic properties than non-eroded soils and this causes the aridity of the eroded site to increase as the eroded areas increase (Rostagno, 1989). Once these areas become degraded, they continue to lose nutrients, water holding capacity, herbaceous cover, and soil particles through erosion (Ayoub, 1998). Erosion of New Mexico's rangelands is the second largest contributor to non-point source pollution and impacts 3200 km of streams in the state (NMWQCC, 1994). The largest contribution to New Mexico water impairment is caused by diffuse sources such as large number of small septic tanks, residual minerals, animal feedlot operations, storage of waste products, urban runoff, and applications of agricultural chemicals (NMWQCC, 1994).

One explanation for eroded rangelands falling short of their production potential is the infertility of rangeland soils. The application of manure to rangelands has the potential to enhance soil properties including increased soil organic matter, increased extractable P, and increased soil moisture, hence increasing the production potential, and consequently, the livestock carrying capacity in addition to other concomitant environmental benefits. The state of New Mexico has approximately 80% of its 16,184,000 ha classified as rangelands (USDA-NRCS, 1997). Most of these rangelands are below their grazing potential, but being grazed to maximum capacity (Wood et al., 1986). Restoration of degraded rangelands depends upon recovery of soil C and plant nutrients (Martinez et al., 2002). Consequently, a goal of range management is to increase plant growth and litter production, which ultimately could lead to increased soil C and nutrient levels (White et al., 1997). However, inorganic fertilizers are costly and quickly lost following application (Westerman and Tucker, 1979). A feasible alternative to chemical fertilizers is the application of manure as organic amendments, which have high organic matter content and can be sources of slow-release of nutrients (Sommers, 1977). Biosolids in the form of sewage sludge have been proven to increase long-term rangeland fertility in New Mexico (Aguilar et al., 1994).

The purpose of this study was to assess the feasibility of the application of dairy manure to rangelands regarding changes in soil properties and P runoff. The application of dairy manure could reverse soil degradation and enhance soil fertility in New Mexico rangelands.

2. Materials and methods

2.1. Study area

This study was conducted in Sierra County, north of Winston, NM adjacent to the Black Range in western New Mexico (33°28′23.7″ N, 107°42′05.9″ W). The study site elevation is approximately 2190 m, with an annual precipitation of 305 mm year^{-1} (Neher, 1984), which comes mostly in the form of late summer rains (July–September). The frost free period at the site ranges between 140 and 180 days, and the average daily temperature is 13 °C (Neher, 1984). The landscape consists of rolling hills and the study site had a slope of approximately 10%. The predominate vegetation type was a blue grama (*B. gracilis* (H.B.K.) Lag. ex Steudel) grassland adjacent to a pinyon pine-juniper (*Pinus edulis* Engelm.-*Juniperus monosperma* (Engelm) Sarg./*J. deppeana* Steud.) woodland. Soils were classified as the Ildefonso soil series, a loamy-skeletal, mixed, mesic, Ustollic Calciorthid with a soil surface layer of gravelly fine formed from a mixed alluvium, and a textural class of sandy loam (Neher, 1984). These soils belong to the dominant soil orders of Calcisols, Cambisols, Luvisols (FAO, 2003). The Natural Resources Conservation Service described it as moderately permeable, low available water capacity, moderate wind and water erosion hazard, moderate runoff, and an available rooting depth of 152 cm (59.8 in.) (Neher, 1984).

In 1993, 12 runoff plots of 25 m × 4 m were established 3 m apart and parallel to the slope of the terrain (Mosley, 1996). Runoff plots were framed with a metal border 30 cm high and 15 cm deep to help keep precipitation and runoff within the plot area and to keep other runoff out of the plots. Each of the plots had a water catchment and container tank (1.96 m diameter and 0.91 m deep) at the lower end of the slope to catch runoff and sediment. The entire study site was fenced with 4-strand, barbed wire fence (120 cm high) to exclude livestock, but allowed access by wild ungulates such as deer, elk, and antelope.

2.2. Rainfall recording

Hourly rainfall data were collected using a tipping bucket rain gauge (TE525) connected to a CR-10x (Campbell Scientific, Logan, UT) data logger with totals recorded every 24 h during the rainy season (June–September) from year 1999 to year 2002.

2.3. Manure disposal

As commonly applied in New Mexico fields, 60–90 days stockpiled manure samples were randomly collected from a dairy near Las Cruces, NM. Twenty samples were composited and analyzed by trace mineral analysis to determine total extractable P (Galyean and May, 1995). We included two application rates, one being a minimal practical rate that should provide soil and plant productivity benefits, the other being a heavy rate that would allow the risks of manure application to soil and runoff to readily be identified. The actual rates of P applied were 0, 54, and 493 kg P ha^{-1} corresponding to a control, a calculated based P removal of healthy blue grama productivity (light), and 10 times the recommended amount as a gross over-application or a disposal application (heavy). A "heavy" application rate is often associated with damage that it can do to plants. Whereas the light rate is considered practical because manure spreading equipment is generally difficult to calibrate to levels below 5 Mg ha. The light rate also provides an acceptable nutrient loading rate that was predicted to supply nutrients for the grass without considered to be excessive. We selected a gross over-application because we wanted to track responses in extreme cases. Application rates were based on P in order to study the potential P runoff. Specific amounts of P application were calculated on P removal on healthy, rain-fed grassland, assuming adequate N (Stavast et al., 2005). Applications on a dry weight basis were 0, 11,739, and 107,174 kg ha^{-1}.

Manure was surface applied to plots by hand, 28–30 June 2000 according to preset rates. Treatments were randomly assigned to the plots. During application, manure samples were collected randomly from each plot and analyzed by trace mineral analysis (Galyean and May, 1995) to determine the actual amount of P applied. Gravimetric moisture content was also measured to determine actual dry matter applied to plots. The actual P application rate was, mean (SD): 0, 54 (2.8), 493 (28) kg ha^{-1}. After application, manure depth was 0.5–1 cm on the light treatment and 6–8 cm on the heavy treatment. Manure completely covered the soil surface, even under the canopy of shrubs. Shrubs on the site are not extensive or expansive, therefore manure covered every square inch of soil, except for that occupied by the stem or stalk of vegetation.

2.4. Runoff quantity and quality measurement

Pre-treatment runoff water was collected weekly in 1999. Following treatment application, runoff water was collected weekly until snowfall in 2000 (July–November), 2001 (June–October) and 2002 (June–October) to determine the amount and quality of runoff water after rainfall. Every plot was delimited with metal plates and had a down gradient plastic collector connected to a bucket to measure runoff quantity. A sample of 1 L was collected and 2 mL of concentrated H_2SO_4 were added to preserve each sample. Another sample of 125 mL was also collected to measure pH, electric conductivity (EC) and turbidity of the water without the effects of the H_2SO_4. The runoff samples were stored in a refrigerator at 2 °C until they were tested. Runoff water pH was tested using a portable pH meter (HANNA Instruments HI 9023), turbidity was tested using a portable turbidity meter (HANNA Instruments HI 93703), and EC was measured using a laboratory conductivity meter (Accumet conductivity cell, Fisher Scientific, Pittsburgh, PA). Sediment concentration in the runoff was determined by centrifuging the samples (Beckman J2-21 centrifuge) at 7000 rpm for 1 h, decanting the water, and then drying the remaining sediment in a drying oven. Sediment was oven dried to a constant weight or a point at which no further weight loss was observed. The dried sediment was weighed. Total phosphorus content of the water was determined using method 365.2 (Eaton et al., 1995).

2.5. Soil samples and measurements

Six soil samples, to a depth of 10 cm, were systematically taken from throughout each plot before manure application and again at the end of the second growing season after manure application. Samples were returned to the lab, sieved to ≤2 mm effective diameter and tested using the saturated paste extract procedure (USDA, 1954). Each experimental unit (plot) was systematically divided into six sections. Within each of the six sections a soil sample below the manure, to a depth of 10 cm, was randomly collected in each of the 12 plots. Pre-application soil samples were collected on May 30, 2000. Post-application samples were collected on September 28, 2001 and October 24, 2002. Samples were air-dried and sieved to ≤2 mm diameter. Saturated pastes were made according to the U.S. Salinity Lab procedure (USSL Staff, 1954). Soil pH was measured on the saturated paste after mixing using a Beckman Φ 72 pH meter. The extract was collected 4 h after mixing and the EC was measured with an Accumet conductivity cell. The extract was also analyzed for sodium (Na), magnesium (Mg), and calcium (Ca) by inductively coupled plasma optical emission spectroscopy (ICP-OES). These elements were then used to calculate the sodium adsorption ratio (SAR) of the saturated paste extract. Soil organic matter was calculated from the organic carbon content analyzed by Walkley–Black method (Nelson and Sommers, 1982) and using a factor 1.7.

Soil moisture and bulk density were measured in the field to a depth of 9 cm using a calibrated Troxler nuclear gauge model 3411-b (Troxler Electronic Laboratories, Research Triangle Park, NC) on July 8, 2000, September 12, 2001 and August 27, 2002. Each plot was divided into six sections starting at the highest part of the slope and moving towards the base of the slope. Within each one of the six sections, a location was selected randomly to measure soil moisture and bulk density. Nuclear gauges transmit gamma radiation through the soil to determine bulk density (Blake and Hartge, 1986) and neutrons transmitted in the soil are used to determine soil moisture. The nuclear gauge was used because it does not disturb the soil as much as other methods. Nuclear gauge is simply rested on the surface of the soil whereas other methods (e.g., soil core method, clod method) involve digging and disturbing the soil. Soil P was determined using the Olsen ($NaHCO_3$) method (Olsen et al., 1954). Soil particle size distribution was measured on the pre-treatment soil samples using the pipette method (Gee and Bauder, 1986) and the results were plotted on a soil textural triangle (USDA-SSDS, 1993) to determine soil textural class. Two samples, one from the top and one from the bottom of the slope, were taken to a depth of 10 cm from each plot and combined to obtain the soil texture for each plot.

2.6. Statistical analysis

Statistical analyses were performed using SAS statistical software version 8.2 (SAS Institute, 2001). All variables were checked for normality using PROC UNIVARIATE (SAS Institute, 1996). Those variables that were not normally distributed were analyzed using PROC NPAR1WAY (SAS Institute, 1996) with the Kruskal–Wallis Test. Analyses were conducted to determine differences among treatments within years. Analysis of variance was used to determine significant differences between treatments within years. Duncan's new multiple range test was used to separate the means at $\alpha = 0.05$ after significance had been determined and contrast analyses were used to test differences between specific treatments or years.

Measurements of soil adsorption ratio and soil electric conductivity were sorted by treatment and year to produce probability of exceedance graphs to analyze the risk of reaching undesirable values.

This study encompassed 3 years (2000–2002). For practical and replication purposes years were renamed to Year 1, Year 2, and Year 3. In addition, for comparison purposes we discuss some measurements recorded in 1999, a year before starting the experiment (Year 0). The rainy season (June–September) coincides with the main growing season in each year.

3. Results and discussion

3.1. Rainfall

Lower precipitation was recorded in Year 1 than in Year 2. These were 207 and 308 mm, during the rainy seasons (June–September), respectively. Precipitation during the rainy season in Year 0 was 331 mm and in Year 3 was 211 mm (Fig. 1). Precipitation in the

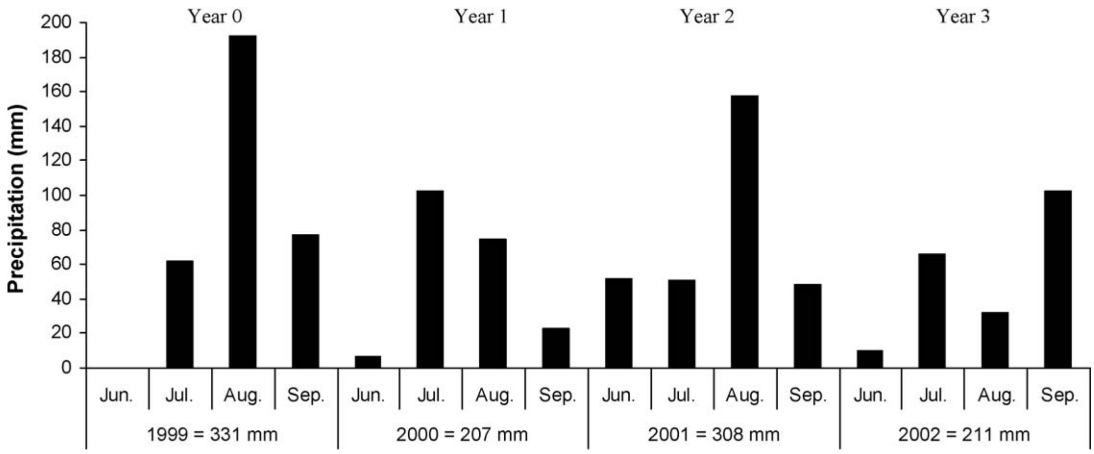

Fig. 1. Monthly precipitation during the rainy season June–September (1999–2002).

study area is on the lower end of what Martin and Berry (1970) recommended (300–800 mm year^{-1}) for application of N fertilizers to be considered beneficial.

3.2. Runoff amount

The amount of runoff was highly variable across time, but there were no significant differences in runoff amounts before the application in Year 0 (data not shown) or in successive years after the manure application in Year 0.

Though non-statistically significant, the trend in our findings has been shown in prior studies that used rainfall simulators and smaller plots (Roberts and Clanton, 1992; Aguilar et al., 1994; Harris-Pierce et al., 1995; White et al., 1997; Persyn et al., 2004).

3.3. Runoff water pH

The pH of the runoff water from all treatments in Year 1 and Year 2 was between 6.6 and 6.8 (Table 1), within the surface water quality standards range of pH for the state of New Mexico (NMWQCC, 2002); however it was lower than those standards in Year 3 for all treatments. Rostagno and Sosebee (2001) also found decreased pH of runoff water after biosolid application. They also showed that the decrease in runoff water pH was inversely proportional to the amount of manure application. Runoff from the heavy application rate was also greater than the control in both years. Runoff water pH was less than the lower limit across both treatments including the control in the third year. Additional information is needed regarding the rain pH in order to understand why the pH was so low in Year 3.

3.4. Runoff electrical conductivity

The EC for all treatments in all years following application was within the maximum New Mexico water quality standard of 1.5 dS m^{-1} for surface waters (NMWQCC, 2002). Post-treatment runoff water EC on the heavy treatment was significantly greater than that of the light and control treatments in Year 1 ($p = 0.021$) and in Year 2 ($p = 0.004$) (Table 1). The EC of the heavy treatment was 5 times greater than the light treatment in Year 1 and 3.7 times greater than the light treatment in Year 2. Elevated soil EC interferes with soil nutrient availability and is detrimental to plant growth. Consequently, heavy applications of manure would diminish the support of plant population in rangeland soils. This finding is consistent with Rostagno and Sosebee (2001) who found increased runoff water EC as biosolid application rates increased. Elevated soil EC because of one manure application is a temporal condition that would tend to return to normal after soluble salts are leached from the root soil layer. Nevertheless, permanent applications of manure might change soil conditions and its characteristics to support plant growth.

3.5. Turbidity

No significant differences were detected in the turbidity of the runoff water between treatments (Table 1). Turbidity levels ranged between 9 and 21 FTU (formazin turbidity unit), which were below

Table 1
Runoff characteristics after dairy manure application on a blue grama rangeland in New Mexico[a].

Year	Treatment	Runoff[b] (L ha^{-1})	pH[b]	EC[b] (dS m^{-1})	Turbidity[b] (FTU)	P[b] (mg L^{-1})	SY[b] (kg ha^{-1})
Year 1 (2000)	Control	39a (19)	6.6a (0.11)	0.09a (0.03)	9.0a (3.1)	0.7a (0.25)	0.6a (0.5)
	Light	39a (57)	6.7a (0.12)	0.12a (0.05)	9.9a (2.8)	2.2b (0.62)	0.6a (0.6)
	Heavy	42a (23)	6.9b (0.13)	0.59b (0.23)	20.6a (12.9)	3.8b (2.61)	0.3a (0.3)
Year 2 (2001)	Control	141a (70)	6.6a (0.10)	0.07a (0.05)	10.5a (5.3)	0.6a (0.22)	17.4a (18.2)
	Light	89a (93)	6.6a,b (0.07)	0.10a (0.05)	8.1a (2.8)	0.6a (0.25)	3.5a (3.1)
	Heavy	85a (106)	6.8b (0.15)	0.37b (0.28)	14.8a (10.66)	1.0b (1.04)	2.8a (5.4)
Year 3 (2002)	Control	123a (83)	6.4a (0.13)	0.05a (0.02)	10.5a (6.18)	0.6a (0.39)	6.2a (7.2)
	Light	43a (43)	6.4a (0.09)	0.04a (0.01)	18.8a (25.57)	0.6a (0.48)	0.8b (0.7)
	Heavy	45a (49)	6.2a (0.18)	0.12a (0.06)	4.4a (1.16)	2.6b (2.4)	0.9b (0.8)

EC, electric conductivity; SY, sediment yield.
[a] Standard deviations of the means in parentheses.
[b] Means in the same column with the same lowercase letter are not significantly ($\alpha = 0.05$) different among treatments within year. Treatments are control = 0, light = 54 and heavy = 493 kg ha^{-1} of P applied in dairy manure.

the New Mexico state surface water quality standard for turbidity of 50 FTU (NMWQCC, 2002).

3.6. Runoff phosphorus

The mean runoff water P concentration from the light and heavy treatments in Year 1 was significantly greater ($p = 0.020$) than the control (Table 1). In Year 2 and Year 3, only the runoff water extractable P from the heavy treatment was significantly greater ($p = 0.011$) than both the control and light treatments. The heavy treatment was 67% greater than the light treatment in Year 2 and 4.3 times greater than the light treatment in Year 3. This is consistent with findings of Kleinman et al. (2005) and Harris-Pierce et al. (1995).

As runoff water P concentration decreases, the amount of readily soluble P also decreases (Vadas et al., 2008). Therefore, the P may have moved from the surface of the soil into the soil profile and may no longer be a concern in runoff within a year after the light application of manure. On the heavy treatment, the effect appeared to last longer, but further study is required to determine the length of time needed to return to background levels.

3.7. Sediment yield

Sediment yield was not significantly different among treatments for Year 1 and Year 2, but it was significantly lower ($p = 0.0001$) for the light and heavy treatments in Year 3. The sediment yield of the control treatment was 7.8 times greater than the light treatment and 6.9 times greater than the heavy treatment in Year 3. The change in sediment production was significantly different between years ($p = 0.0001$). Running a contrast test between Year 1 and Year 2 showed a significant difference ($p = 0.027$). However, a contrast test between Year 0 and Year 2 showed no significant difference. Most of the difference between Year 1 and Year 2 can be attributed to one very intense rainstorm in Year 2 (August 24, 2001) when there was 31.75 mm of precipitation in less than 1 h. This suggests that during normal rainfall events the manure does not affect sediment yield, but during more intense storms it keeps soil in place better relative to the control. Increased vegetation production and biomass, which holds the soil in place on the amended plots, may also explain lower sediment yield on these plots relative to the control (Stavast et al., 2005). Gilley et al. (1999) also found no significant difference in sediment yield, but noted that it tended to be less on amended soils than on unamended soils. However, Harris-Pierce et al. (1995) found significant increases in runoff sediment following biosolid application to a rangeland. Differences among study results can be explained mostly because the type of organic matter applied. Gilley et al. (1999) used stockpiled feedlot manure and we used dairy manure of open lot dairy operations, which have similar physical and chemical properties. Harris-Pierce et al. (1995), however, used sewage sludge, which has concomitant differences with livestock manure. We conclude then that, in rangeland soils, livestock manure amendments keep soil particulates in place better than sewage sludge.

3.8. Soil pH

Dairy manure application increased soil pH by about 1 U, from 6 to 7 (Table 2). The increase in pH with the treatments may have affected soil chemical reactions and cation exchange capacity (CEC). Increases in pH increase the CEC of the soil due to increase of negatively charged hydroxyl groups in the soil which will be able to bind with the positively charged cations. The increase in pH found in this study is contradictory to the findings of Aguilar et al. (1994) who recorded a decrease in soil pH on a sewage sludge application to semiarid grassland in central New Mexico. The pH increase is also contradictory with Martinez et al. (2003) who found that the soil pH to remain steady with bio-waste applications of up to 120 Mg ha^{-1}. In all, applications were similarly surfaced applied, consequently the differences are attributed to the difference in the type of manure or biosolid application in association with the soil original pH in each one of the studies. Aguilar et al. (1994) used sewage sludge (pH 6.5) applied to a soil with pH 7.6 and therefore soil pH decreased. Martinez et al. (2003) used biosolid (pH 8.6) and composted municipal solid wastes (pH 6.7) applied to a soil with pH 8.3 and therefore soil pH remained steady. We used dairy manure (pH 8.57) applied to a soil with pH 6, which explains the increase in soil pH.

3.9. Soil electrical conductivity

Soil EC in the heavy treatment in Year 2 and Year 3 was significantly greater ($p = 0.007$) than the control and light treatments, which suggests that gross over-application of manure increased soil EC (Table 2). Soil EC of the heavy treatments was 8 and 9 times greater than the light treatments in Year 2 and Year 3, respectively. Soil EC of the heavy treatments was 33 and 36 times greater than the control treatments in Year 2 and Year 3, respectively. No differences were detected between the light and control treatments, which suggest that application at the light rate does not significantly affect soil EC. These results agree with those of Martinez et al. (2003) who found at rates of 80 and 120 Mg ha^{-1} of manure application, soil EC differed significantly from applications of 40 Mg ha^{-1} and a control, although the

Table 2
Soil characteristics after dairy manure application on a blue grama rangeland in New Mexico[a].

Year	Treatment	pH[b]	EC[b] (dS m^{-1})	SAR[b]	SOM[b] (%)	Soil P[b] (mg kg^{-1})	BD[b] (Mg m^{-3})	Moisture[b] (%)
Year 1 (2000)	Control	6.0a (0.2)	0.32a (0.05)	0.34a (0.05)	3.5a (0.2)	20.3a (7.1)	1.2a (0.1)	3.5a (0.2)
	Light	6.0a (0.2)	0.32a (0.05)	0.38a (0.06)	3.3a (0.2)	16.2a (6.6)	1.2a (0.0)	3.3a (0.2)
	Heavy	6.2a (0.1)	0.33a (0.04)	0.34a (0.06)	3.4a (0.3)	17.0a (3.3)	1.3a (0.1)	3.4a (0.3)
Year 2 (2001)	Control	6.4a (0.4)	0.23a (0.03)	0.38a (0.11)	3.1a (1.0)	13.4a (8.1)	1.2a (0.0)	3.1a (1.0)
	Light	7.0b (0.1)	0.97a (0.12)	2.26a (0.80)	4.2a (1.1)	80.2a (26.9)	1.1b (0.0)	4.2a (1.1)
	Heavy	7.0b (0.4)	7.76b (2.86)	7.36b (2.01)	4.7a (0.7)	271.4b (197.5)	1.1b (0.1)	4.7a (0.7)
Year 3 (2002)	Control	6.3a (0.2)	0.22a (0.06)	0.23a (0.07)	3.1a (0.5)	17.2a (7.5)	1.1a (0.1)	3.1a (0.5)
	Light	6.8b (0.2)	0.83a (0.28)	1.38a (0.74)	4.0b (0.2)	81.3b (26.1)	1.1a (0.0)	4.0b (0.2)
	Heavy	6.8b (0.1)	7.92b (2.14)	6.34b (1.34)	4.3b (0.4)	135.6c (27.8)	1.0b (0.0)	4.3b (0.4)

EC, electric conductivity; SAR, sodium adsorption ratio; SOM, soil organic matter; BD, bulk density.
[a] Standard deviations of the means in parentheses.
[b] Means in the same column with the same lowercase letter are not significantly ($\alpha = 0.05$) different among treatments within year. Treatments are control = 0, light = 54 and heavy = 493 kg ha^{-1} of P applied in dairy manure.

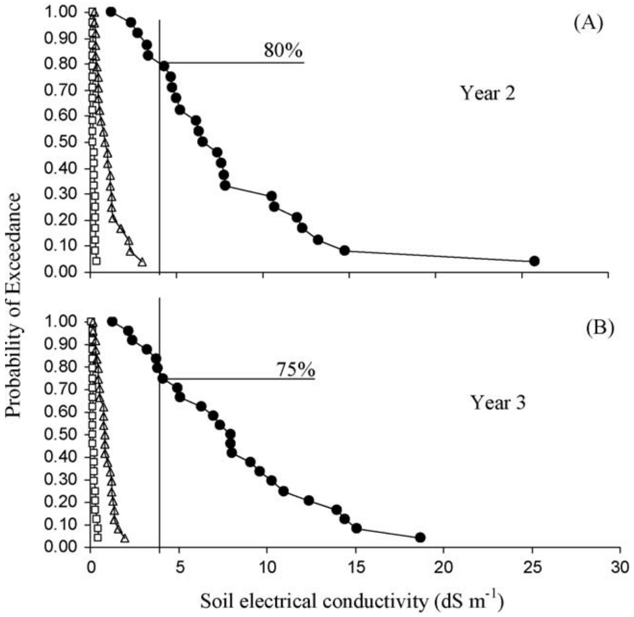

Fig. 2. Probability of exceedance of soil electrical conductivity for control (squares), light (triangles), and heavy (solid circles) treatments of dairy manure 1 year after application (Year 2; A), and 2 years after application (Year 3; B). Vertical lines indicate 4.00 dS m^{-1} that is considered to be the threshold at which soils are saline.

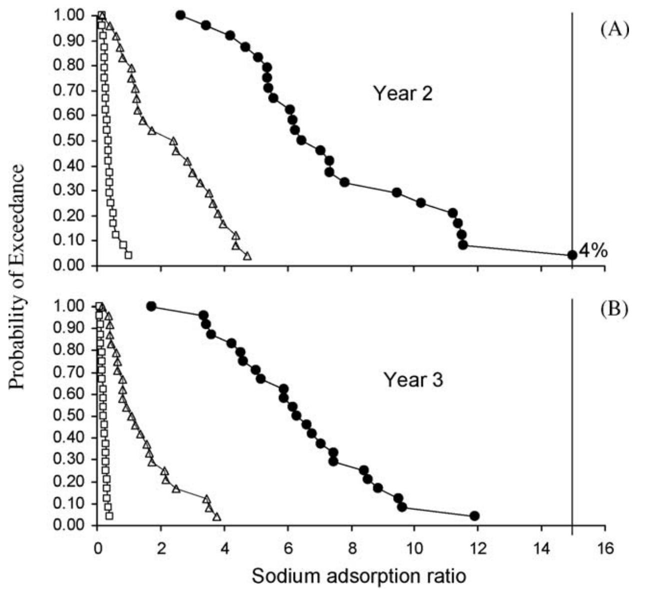

Fig. 3. Probability of exceedance of soil sodium adsorption ratio for control (squares), light (triangles), and heavy (solid circles) treatments of dairy manure 1 year after application (Year 2; A), and 2 years after application (Year 3; B). Vertical lines indicate 15 sodium adsorption ratio that is considered to be the threshold at which soils are sodic.

soluble salts did not exceed the 4.00 dS m^{-1} that would classify the soil as saline (Rhoades and Loveday, 1990). Although the light treatments did not become saline, soil EC in the heavy treatment in Year 2 and Year 3 (7.76 and 7.92 dS m^{-1}) exceeded the threshold (4.00 dS m^{-1}) above which a soil is considered to be saline (NMWQCC, 2002). Soil soluble salts exceeded 4.00 dS m^{-1} 80% of the time on Year 2 (Fig. 2A) and 75% of the time on Year 3 (Fig. 2B), which indicates that over-application of dairy manure could be detrimental to plant growth for at least 2 years after application. Increases in soil salinity may limit the growth of some species of range plants that are not salt tolerant (Blaylock, 1994). Sweeten and Mathers (1985) also found an increase in soil salinity after manure application. However, Aguilar et al. (1994) hypothesized that in coarser soils found in New Mexico's rangelands, the salinity problem would be short-lived, because it could be flushed out of the sandy soil with rain.

Soil EC from Year 1 to Year 2 and to Year 3 showed a significant increase ($p = 0.005$) in the heavy treatment compared to the light and control treatments. Exactly how long this soil will remain saline is unknown. Results from White et al. (1997) suggested that following this initial increase the EC would decrease to near untreated levels after 8 or 9 years.

3.10. Sodium adsorption ratio

The SAR was significantly greater ($p < 0.001$) on the heavy treatment in Year 2 and Year 3 than the control or the light treatments, but no differences were detected between the light and control treatments (Table 2). The SAR on the heavy treatment was 4.6 and 27 times greater than the SAR on the light and control treatments, respectively. Although the SAR on the heavy treatment was 7.36 in Year 2 and 6.34 in Year 3, it did not exceed the value of 15 for being considered a sodic soil (U.S. Salinity Laboratory Staff, 1954). There was one soil sample (4%) on the heavy treatment exceeding this value (Fig. 3A) in Year 2, although no observation exceeded SAR 15 (Fig. 3B) in Year 3. The increase in sodium on the heavy treatment soil may affect the soil water infiltration because of the osmotic effects of sodium on the soil water retention (Goncalves et al., 2007). Sodium ions cause the soil particles to deflocculate or disperse for what soils are hard and cloddy when dry and tend to crust. Therefore, water infiltration is reduced because soil dispersion hardens and blocks water infiltration. Elevated levels of sodium on soil may consequently increase runoff and soil erosion.

3.11. Soil organic matter

There were no significant differences in percentage SOM between treatments in Year 1 and Year 2. This may be due to the organic matter not breaking down and entering the soil profile in such a short period of time. However in Year 3, the light and heavy treatments had significantly ($p < 0.001$) greater soil organic matter than did the control (Table 2). The treated plots (pooled means) had a 34% increase in measured soil organic matter over the control plots. This is similar to Martinez et al. (2003) and Billings et al. (2006) where time and environmental conditions were favorable for the incorporation of manure and plant residues into the soil.

3.12. Soil phosphorus

The light and control treatments showed significantly less soil P than the heavy treatment ($p = 0.029$) in Year 2 (Table 2). In Year 3, soil extractable P in the heavy treatment was significantly greater than the light treatment and the light treatment was significantly greater than the control. Phosphorus content was greatest on the heavy treatment followed by the light and then the control treatment. Long-term applications of animal manures will often result in an increase in soil test P (Sharpley et al., 1993; Kingery et al., 1994; Motschall and Daniel, 1982). The heavy rate of manure application to the New Mexico rangeland resulted in increased soil test P in just 2 years (Table 2). This is undoubtedly a function of the P loading rate from the heavy application. The light rate plots took an additional year before soil test P levels rose above the no manure applied plots. After 2 years the heavy treatment soil test P was 7.9 times greater than the control treatment. The light treatment also had an increase in soil test phosphorus by Year 3 (Table 2). More P from the light rate had been applied than could be used by the grass resulting in a 4.7 fold increase in soil test P. This could be a benefit for plant growth over time since many soils are P deficient (Massie, 2001), but close attention should be paid to runoff water P content. Bell et al. (2006) experienced a 44% increase in soil P levels 2-year-after application of manure to a rangeland ecosystem. Rain, plant growth and use of P were probably a factor in differences we see between the two studies. Applying manure as a P source could certainly be achieved with lighter applications.

The heavy treatment had 1.7 times higher extractable P than the light treatment and the light treatment had 4.7 times higher extractable P than the control treatment in Year 2. Results in Year 1 and Year 2 were consistent with those of Walter et al. (2000) and Bell et al. (2006) who found a proportional increased concentration in soil P after application of manure or biosolid in a rangeland ecosystem, although differed in Year 3 in that the light treatment was greater than in the control. This increase in soil P is important on New Mexico soils because these soils are typically P deficient (Massie, 2001).

3.13. Bulk density

Bulk density of the soil in Year 2 was significantly lower ($p = 0.017$) in the light and heavy treatments than in the control (Table 2). In Year 3, the heavy treatment was significantly lower ($p = 0.005$) than the light and control treatments. This lower bulk density may promote greater rainfall infiltration on the manure treated plots, due to an increased porosity. The decrease in soil bulk density following the application of the manure is consistent with the reports of Smith et al. (1937), Punshon et al. (2002), and Herrick and Lal (1995). Bulk density reflects the soil's ability to take in water and afford structural support of plants. Bulk density is dependent on soil texture, organic matter, and physical structure. Ideal bulk densities for plant growth range from 1.10 g/cm^3 for clayey soils to 1.6 g/cm^3 for sandy soils. However, if bulk densities exceed 1.47 g/cm^3 for clayey soils or 1.8 g/cm^3 for sandy soils there could be restriction in root growth (USDA-NRCS, 2008). This is only a 0.2 g/cm^3 difference in sandy soils for an ideal versus restrictive bulk density. Differences among the treatments (Table 2) suggests that heavy application of manure can reduce the bulk density of rangeland soil over time. While the bulk density in these plots were not considered restrictive, highly trafficked areas in rangeland with greater bulk densities may benefit from land applied manure.

3.14. Moisture

Post-manure application soil moisture was not significantly different among treatments in Year 1 or Year 2 (Table 2). However, it was significantly different ($p = 0.039$) between the applied and control plots in Year 3, although there was no significant difference between the heavy and light treatments. Soil moisture on treated plots increased 34% in the third year. This improvement can be attributed to increased soil organic matter as a result of applying manure. There was also a mulching effect due to the manure placement over the soil surface that could have reduced the amount of evaporation from the plots. Hahm and Wester (2004) found similar results in the Chihuahuan desert. Increased soil water storage can certainly have an impact on primary productivity of rangeland.

4. Conclusions

The application of dairy manure at the recommended rate of 54 kg P ha^{-1} as a soil amendment is a promising practice to enhance rangeland soil and runoff properties and to dispose unwanted manure. Application at this recommended rate did not promote increased runoff salinity, runoff P, soil salinity, or soil sodium which was observed with the heavy application treatment of 450 kg P ha^{-1}. Runoff P was significantly higher and more persistent in the heavy treatment, which did not return to original conditions as the light treatment did after 2 years. Therefore, the light or recommended application rate provided a series of benefits without the detrimental effects of the heavy manure treatment including decreased sediment runoff, increased soil organic matter, increased extractable P, and increased soil moisture. Consequently, it can be recommended that dairy manure can be safely applied at light rates to conserve and enhance rangeland soil properties and their herbaceous productivity. Manure disposal at heavy rates used in the study are unsafe. Further research is required to find out if other safe disposal rates exist between the light and heavy rates. With 355,000 dairy cows in New Mexico producing 1.06 billion kg of dry manure annually, the soil properties of 90,600 ha of New Mexico rangelands could be improved at the recommended rate of manure P of 54 kg P ha^{-1} that is equivalent to 11,740 kg ha^{-1} of dry dairy manure. Further research is needed to determine the frequency at which multiple light applications might be recommended. In addition to exploring proper rates and frequencies of application, research is also needed to optimize possible pre-application treatment of manure to facilitate transportation and application as well as the economics (i.e., economies of scale and transportation) of the entire process. However, results from this study indicate that light applications of dairy manure to rangelands can enhance New Mexico's rangelands and help with the dairy manure disposal problem.

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