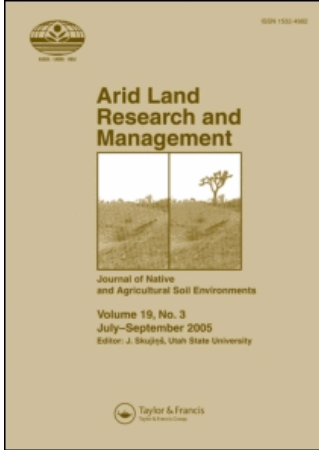


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Arid Land Research and Management

Publication details, including instructions for authors and subscription information:
<http://www.informaworld.com/smpp/title~content=t713926000>

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Online Publication Date: 01 April 2007

To cite this Article: Brenton, Cynthia M., Fish, Ernest B. and Mata-González, Ricardo (2007) 'Macronutrient and Trace Element Leaching Following Biosolids

Application on Semi-arid Rangeland Soils', *Arid Land Research and Management*, 21:2, 143 - 156

To link to this article: DOI: 10.1080/15324980701267783

URL: <http://dx.doi.org/10.1080/15324980701267783>

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The objective of this study was to quantify the leachate concentration of macronutrients and trace elements obtained through intact soil columns containing two rangeland soils with different texture and amended with biosolids. This was done to evaluate the possibility that surface application of biosolids could adversely affect subsurface water quality via leaching. Biosolids were applied on the surface of the soil columns at 0 (control), 7, 18, 34, or 90 Mg ha⁻¹ in dry basis. Results indicated that biosolids did not increase NO₃⁻-N leaching, except for the application of 90 Mg ha⁻¹ in the Stellar soil (Calciargid), the finer-textured soil. In the Armesa soil (Haplocalcid), the coarser-textured soil, all leachate NO₃⁻-N concentrations were higher than the maximum contaminant limit (MCL) for drinking water established by USEPA, irrespective of biosolids treatment. Orthophosphate leaching occurred mostly in the Stellar soil and was favored by biosolids application. Of the trace elements that are regulated by USEPA, Cd, Ba, Cr, and Be were found below the MCL for drinking water irrespective of the biosolids application rate or soil type. The application of 90 Mg ha⁻¹ of biosolids represented a significantly higher potential of leaching for many elements and compounds (NO₃⁻-N, SO₄⁼, Cl⁻, Ca, K, Mg, Na, and Sr) than applications of 34 Mg ha⁻¹ or lower. In general, the application of biosolids up to 34 Mg ha⁻¹ did not pose potential adverse effects for subsurface water quality.

Keywords desert soil, heavy metals, nitrogen leaching, soil amendment, subsurface water quality

Wastewater treatment has multiple benefits and is a pressing need in growing cities around the world. An additional benefit of wastewater treatment is the beneficial use of the resulting biosolids in land application, which is becoming common practice in

Received 29 August 2006; accepted 2 February 2007.

The authors would like to acknowledge the assistance of R. E. Sosebee, D. B. Wester, R. E. Zartman, R. S. Lutz, C. Moffet, M. Benton, R. Gatewood, P. Jurado, R. Baptista, and E. Flores. The support of Merco Joint Venture, providing biosolids and funding for this study is also appreciated. This is contribution T-9-1103 of the College of Agricultural Sciences and Natural Resources, Texas Tech University, Lubbock, TX.

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the world due to the potential recovery of nutrients and incorporation into degraded soils (Mata-González et al., 2004). Semi-arid rangelands are ideal locations for biosolid land application because soils from these areas are usually low in nutrients and their typically high pH and low moisture tend to reduce the risk of trace element contamination (White et al., 1997; Wester et al., 2003).

The benefits of municipal biosolid application to semi-arid rangelands have been amply documented (Fresquez et al., 1990; Benton and Wester, 1998; Pierce et al., 1998; Jurado and Wester, 2001; Rostagno and Sosebee, 2001; Mata-González et al., 2002, 2004; Martinez et al., 2003; Moffet et al., 2005). Issues remain concerning the safety of biosolid application, however, due to the potential leaching of nutrients or trace elements to deeper soil layers and groundwater (Keller et al., 2002; McLaren et al., 2004; Pierzynski and Gehl, 2005).

Early reports indicated that metal mobility through soil columns amended with biosolids was minimal and little risk of groundwater contamination existed (Giordano and Mortvedt, 1976; Emmerich et al., 1982). However, these studies were conducted in homogenized soil columns that may have different hydraulic properties than intact soil columns (Camobreco et al., 1996). Other studies have attempted to evaluate leaching of macronutrients and trace elements measuring concentrations at different soil depths and using mass balance, but questions remain as to the potential lateral movement of elements and the metal extractability from soils (Keller et al., 2002). Despite its paramount importance, few direct measurements of the quality of soil solutions or drainage waters in soils treated with biosolids have been reported in intact columns (Keller et al., 2002; McLaren et al., 2004) and to our knowledge no reports exist on soils from arid or semi-arid regions.

The objective of this study was to measure the concentration of macronutrients and trace elements in water leached through intact columns of two semi-arid rangeland soils amended with different levels of biosolids. Our goal was to evaluate the possibility that surface application of biosolids may increase the downward movement of macronutrients or trace elements towards deeper soil layers, potentially affecting the quality of subsurface waters. We tested the hypothesis that the different rates of biosolid application would result in differences in the leachate concentration of macronutrients and trace elements in the leachate and that leachate concentrations would increase with increasing biosolids rates.

Materials and Methods

Study Area

The experiment took place on the Sierra Blanca Ranch, located about 10 km north of Sierra Blanca, Texas (31°16'N, 105°22'W). The ranch is located in the Trans-Pecos region of Texas where the general vegetation type is desert grassland. Elevation for the research site is about 1430 m above sea level. The long-term annual precipitation average is 310 mm, occurring mainly from July to September. The mean annual temperature is 18°C, but temperatures of 38°C during the summer are common in the area.

Two sites with different soil characteristics were selected for this study. One site had Armesa taxadjunct fine sandy loam soil, which is a fine-loamy, carbonatic, thermic Ustic Haplocalcid (B. L. Allen and C. Moffet, personal communication). The first (A1, 0–11 cm) and second (A2, 12–23 cm) horizons are fine sandy loams.

Table 1. Baseline chemical characteristics of untreated Armesa and Stellar soils (0 to 30 cm depth)

Parameter	Armesa	Stellar
Ca (meq l ⁻¹)	4.42	2.33
Electrolytic conductivity (dS m ⁻¹)	0.46	1.66
K (mg kg ⁻¹)	37.33	27.00
Mg (meq l ⁻¹)	0.66	0.82
Na (meq l ⁻¹)	1.55	10.01
NO ₃ ⁻ -N (mg kg ⁻¹)	4.60	22.20
Organic matter (g kg ⁻¹)	7.00	8.50
P (mg kg ⁻¹)	2.60	4.27
pH	7.53	7.54
Sodium adsorption ratio	0.97	7.98
Total Kjeldahl Nitrogen (mg kg ⁻¹)	496.75	881.67

The third (Btk, 24–54 cm) horizon is a sandy clay loam, while the fourth (Bk 55–75+ cm) horizon is a fine sandy loam. On this site, the vegetation was dominated by *Bouteloua eriopoda* (Torr.) Torr. (black grama), *Bouteloua gracilis* (H.B.K.) Lag. Ex Steud. (blue grama), *Yucca elata* Engelm. (soap tree yucca), and *Ephedra trifurca* Torr. (Mormon tea). The other site had Stellar taxadjunct loam soil, which is a fine, mixed, superactive, thermic Ustic Calcic Argid (Casby-Horton, 1997). The A (0–7 cm) horizon is a loam that overlies Bt1 (7–33 cm) and Bt2 (33–57 cm) horizons of clay soil. Therefore, although the Stellar soil is loam on the surface it overlies an argillic layer. On this site, the main vegetation is composed of *Hilaria mutica* (Buckl.) Benth. (tobosagrass), *Prosopis glandulosa* var. *glandulosa* Torr. (mesquite), *Ziziphus obtusifolia* (Hook. ex. Torr. & Gray) Gray (lote bush), and *Gutierrezia sarothrae* (Pursh) Britt. & Rusby (snakeweed). Some chemical characteristics of the Armesa and Stellar soils are presented in Table 1 for general purposes of categorization and contrasting of the soils. The soil analyses were made on samples obtained from 0–30 cm depth and do not reflect the differences in soil horizons. Soil analyses were conducted by the Soil, Water, and Air Testing (SWAT) Laboratory of New Mexico State University, Las Cruces, NM. Organic matter was determined by the Walkley-Black procedure (Nelson and Sommers, 1996) and total N (Total Kjeldahl Nitrogen) by macro Kjeldahl (Bremner, 1996). Available P was obtained by extraction with NaHCO₃ (Olsen and Sommers, 1982). Electrical conductivity and pH were determined in a solution extracted from a saturated paste (Richards, 1954). Na, Ca, Mg, and K were determined by inductively coupled plasma and sodium adsorption ratio (SAR) was calculated following Richards (1954). NO₃⁻-N was determined by Cd reduction (Mulvaney, 1996).

Lysimeter Preparation and Installation

To test water quality after biosolids application, the experiment was designed to allow water to leach through treated soil columns and ultimately collect the leachate for chemical analyses. To achieve this, undisturbed soil columns encased in PVC cylinders of 25.4 cm inside diameter were obtained from the two sites. The soil

columns were obtained by inserting the PVC cylinders into bare soil previously wetted to reduce its frictional resistance to penetration. A backhoe was used for pushing each cylinder vertically into the soil. The goal of obtaining intact columns was to preserve the soil structure and hydraulic properties as much as possible.

A backhoe was also used to remove the soil surrounding the cylinders and subsequently to lift the cylinders containing the intact soil column into a truckbed for transport to a rainout shelter laboratory. Care was taken to prevent compaction of the soil columns avoiding backhoe movement on the top of the columns. The PVC cylinders were 90 cm long, but the depth of the soil columns obtained was variable. For the Armesa soil, the depth of the soil columns obtained varied from 63 to 85 cm (mean 75 cm, standard deviation 6.4 cm). For the Stellar soil, the depth of the soil columns obtained varied from 22 to 36 cm (mean 30 cm, standard deviation 2.7 cm) because a heavy clay layer at about 30 cm depth restricted the insertion of the cylinders. Twenty-five lysimeters were obtained from each soil type.

In the laboratory, each lysimeter was cleaned and gently positioned on squared plexiglass sheets (30 cm × 30 cm). The plexiglass sheets were attached to the base of the cylinder by making a water-tight seal (silicon caulking). The plexiglass sheets had been drilled with 13 holes, 0.64 cm in diameter to allow the passage of the leachate from the soil column while keeping a minimal soil loss. The lysimeters were placed on wooden racks specifically designed to hold the lysimeters in an upright position and to allow access to the lysimeter base for leachate collection. After installation, water was added to the lysimeters to approximate field capacity of the soils.

Treatments and Experimental Design

The treatments consisted of five biosolids application levels: 0, 7, 18, 34, and 90 Mg ha⁻¹ (dry basis) applied on the surface of the soil columns. 0 Mg ha⁻¹ was the control, 7 Mg ha⁻¹ was the initial regulated rate by the Texas Natural Resources Conservation Commission (TNRCC), 18 Mg ha⁻¹ is the full agronomic rate (Water Environment Federation, 1997), and 34 Mg ha⁻¹ is a rate commonly used in previous biosolid studies in west Texas (Jurado and Wester, 2001; Rostagno and Sosebee, 2001; Moffet et al., 2005). The highest level of application (90 Mg ha⁻¹) was selected for research purposes to establish an upper limit to the response of biosolids since it is considered an excessive level for commercial application.

No inorganic fertilizer was applied to any of the treatments. Each treatment was replicated five times and randomly assigned to the lysimeters. The lysimeters were arranged in a completely randomized design. Biosolids were applied in March 1994 to the Stellar soil and in May 1994 to the Armesa soil. No plants were grown in the experimental lysimeters.

The biosolids used in this experiment were provided by a private contractor that land-applied biosolids from New York City to rangelands at the Sierra Blanca Ranch. Biosolids were produced by anaerobic digestion in a residential wastewater treatment facility and met the class-B criteria to be applied on agricultural lands and reclamation areas. The chemical composition of the biosolids (Table 2) was determined by the SWAT Laboratory of New Mexico State University, Las Cruces, NM. The chemical composition of biosolids was determined in five samples which were taken immediately after application and kept frozen until they were taken to the SWAT Laboratory. Biosolids TKN was analyzed by macro-Kjeldahl (Bremner,

Table 2. Chemical characteristics of the biosolids applied to the lysimeters containing Armesa and Stellar soil

Parameter	Armesa	Stellar
Al (g kg ⁻¹)	9	8
B (mg kg ⁻¹)	40	37
Ca (g kg ⁻¹)	19	23
Cd (mg kg ⁻¹)	9	4
Cu (mg kg ⁻¹)	872	430
Fe (g kg ⁻¹)	21	29
K (g kg ⁻¹)	1	1
Mg (g kg ⁻¹)	7	9
Mn (g kg ⁻¹)	1	1
Ni (mg kg ⁻¹)	47	12
P (g kg ⁻¹)	16	21
Pb (mg kg ⁻¹)	236	4
Total Kjeldahl Nitrogen (g kg ⁻¹)	35	37
Zn (mg kg ⁻¹)	887	1185

1996). The remaining elements were determined by inductively coupled plasma-atomic emission spectrometry (USEPA, 2001).

Leaching Process and Analysis

Potable water (Table 3) was used for the leaching process. Water was applied to each lysimeter simulating rainfall by using plastic bottles with a sprinkler device. There were two leaching events for every soil type. The first leaching event took place immediately after biosolids application, in March 1994 for the Stellar soil and in May 1994 for the Armesa soil. The second leaching event for the Stellar soil was in June 1994, 110 days after the first event. For the Armesa soil, the second leaching event was in July 1994, 60 days after the first event. In order to approximate soil moisture to field conditions, 300 ml of water were added between the first and second leaching events. The chemical characteristics of the water used in each leaching event were analyzed from five water samples. The methods for water analysis were the same as for leachate analysis. Water was added to the lysimeters as necessary to produce about 1 liter of leachate for laboratory analysis. The actual amount of water applied varied in each lysimeter, leaching event, and soil. For the Armesa soil the average water used was 3097 ml (standard deviation 681 ml), while for the Stellar soil the average water used was 5530 ml (standard deviation 916 ml). The averages of water used were equivalent to 61 mm of rainfall for the Armesa and 109 mm for the Stellar in 24 h with no runoff, representing 20% and 35% of the average annual total precipitation.

Part of the collected leachate was used to analyze Cl⁻, NO₃⁻-N, orthophosphate, pH, and SO₄⁼ concentrations with a Hach DR-EL5 apparatus (Hach Chemical Company, Loveland, CO), which includes spectrophotometry and titration. Chloride concentration was estimated by titration with mercuric nitrate. Nitrate-N was estimated by Cd reduction, and orthophosphate was estimated by ascorbic acid

Table 3. Chemical characteristics of the water used for the leaching process. Average of 10 samples

Component	mg l ⁻¹
NO ₃ ⁻ -N	1.83
pH	8.16
Orthophosphate	0.20
SO ₄ ⁼	83.40
Cl ⁻	23.70
Ag	0.002
Al	<1.00
As	<0.05
Ba	0.12
Be	<0.001
Ca	17.52
Cd	0.002
Cr	0.02
Cu	0.01
Fe	<1.00
K	5.00
Mg	8.36
Mn	<0.01
Mo	0.01
Na	131.75
Ni	<0.01
Pb	<0.05
Sr	0.36
V	0.02
Zn	0.31

reduction both followed by spectrophotometry. pH was analyzed colorimetrically by spectrophotometry following addition of a wide range pH indicator solution. SO₄⁼ was analyzed by measuring turbidity of barium SO₄⁼ precipitate. Another part of the leachate was collected into 125-ml bottles, preserved with six drops of concentrated nitric acid and shipped to a commercial lab (Chemex Labs, Inc., Tucson, AZ) for analysis of trace elements. The metals analyzed were Ag, Al, As, Ba, Be, Ca, Cd, Cu, Cr, Fe, K, Mg, Mn, Mo, Na, Ni, Pb, Sr, V, and Zn. The metal concentrations were determined by inductively coupled plasma-atomic emission spectrometry (USEPA, 2001).

The objective of having more than one leaching event was to compare water quality of the leachate as influenced by freshly applied and aged biosolids. A comparison of the two leaching events in this study, however, resulted in no consistent differences in water quality for the different parameters tested (Brenton, 1995). Therefore, the results of the two leaching events were combined, doubling the number of replications to 10. Since we were interested in testing potential differences among specific biosolid application rates, data were analyzed by one-way analysis of variance at P < 0.05 and mean separation was performed by protected Fisher's LSD test.

Results

Armesa Fine Sandy Loam Soil

The leachate concentration of NO_3^- -N was not affected by biosolid application (Table 4). However, all treatments, including the control, produced leachate with higher NO_3^- -N concentrations than the maximum contaminant level (MCL) established by USEPA (2004) for drinking water (Table 5). Only two elements, Ba and K, were affected by biosolid application. The concentration of Ba in drinking water is regulated by USEPA (Table 5), but the highest concentration of Ba in the leachate was one-fifth of the MCL. The concentration of K in drinking water is not regulated by USEPA. For both elements, the highest level of biosolids application (90 mg ha^{-1}) produced higher concentrations than the other biosolid levels, while the

Table 4. Concentration of compounds and elements (mg l^{-1}) in the leachate of the Armesa columns treated with different levels of biosolids. Average of 10 replications

Variable	Biosolids level (Mg ha^{-1})				
	0	7	18	34	90
NO_3^- -N	13.78	18.65	20.67	13.68	20.31
pH	8.50	8.57	8.59	8.58	8.59
Orthophosphate	0.28	0.38	0.33	0.32	0.55
$\text{SO}_4^{=}$	93.10	95.70	105.70	102.00	120.50
Cl^-	36.70	37.80	45.55	43.85	48.90
Ag	0.001	0.001	0.002	0.002	0.001
Al	<1.00	<1.00	<1.00	<1.00	<1.00
As	<0.05	<0.05	<0.05	<0.05	<0.05
Ba	0.14 a	0.23 a	0.16 a	0.21 a	0.38 b
Be	<0.001	<0.001	<0.001	<0.001	<0.001
Ca	68.10	76.30	72.80	65.30	108.00
Cd	0.002	0.001	0.001	0.001	0.003
Cr	0.02	0.03	0.02	0.02	0.02
Cu	0.01	0.01	0.01	0.01	0.01
Fe	<1.00	<1.00	<1.00	<1.00	<1.00
K	5.00 a	5.00 a	5.00 a	5.00 a	7.00 b
Mg	23.20	23.85	25.20	27.55	31.10
Mn	0.01	0.01	0.01	0.01	0.02
Mo	0.01	0.01	0.01	0.01	0.01
Na	46.60	38.80	64.60	63.60	43.20
Ni	0.01	0.01	0.03	0.02	0.01
Pb	<0.05	<0.05	<0.05	<0.05	<0.05
Sr	1.86	1.86	1.98	1.86	2.24
V	0.01	0.01	0.01	0.02	0.01
Zn	0.18	0.15	0.16	0.17	0.18

Different letters indicate differences ($P < 0.05$) between biosolids rates for a given variable. Means of variables that are not followed by letters were not significantly affected by biosolid application.

Table 5. Maximum contaminant limits (MCL), action levels, and secondary drinking water regulations (SDWR) established for drinking water by USEPA (2004)

Parameter	mg l ⁻¹
MCL ^a	
As	0.01
Ba	2.00
Be	0.004
Cd	0.005
Cr	0.10
NO ₃ ⁻ -N	10.00
Action level ^b	
Cu	1.30
Pb	0.015
SDWR ^c	
Ag	0.1
Al	0.05–0.20
Cl ⁻	250
Fe	0.3
Mn	0.05
SO ₄ ⁼	250
Zn	5

^a MCL, the highest level of a contaminant that is allowed in drinking water.

^b Action level, the concentration of a contaminant, which if exceeded, triggers treatment or other requirements that a water system must follow.

^c SDWR, nonenforceable federal guidelines regarding cosmetic or aesthetic effects of drinking water.

application of biosolids up to 34 Mg ha⁻¹ produced no differences in water quality with respect to the control. Five elements, Al, As, Be, Fe, and Pb, were below the detection limits (1, 0.05, 0.001, 1, and 0.05 mg l⁻¹, respectively) and therefore, their actual concentrations are uncertain.

Stellar Loam Soil

More water quality parameters were affected by biosolid treatments in the Stellar soil than in the Armesa soil (Table 6). Application of 90 Mg ha⁻¹ of biosolids produced a higher leachate NO₃⁻-N concentration (practically reaching the MCL) than the other biosolid application rates. However, biosolid applications of 7, 18, and 34 Mg ha⁻¹ did not produce differences in NO₃⁻-N leachate concentration with respect to the control.

Application of biosolids at any rate resulted in higher leachate orthophosphate concentrations than the control, but there were no differences among application rates (Table 6). The SO₄⁼ concentration tended to increase with the increase in biosolid rate, but all the concentrations were below the secondary drinking water

Table 6. Concentration of compounds and elements (mg l^{-1}) in the leachate of the Stellar columns treated with different levels of biosolids. Average of 10 replications

Parameter	Biosolids Level (Mg ha^{-1})				
	0	7	18	34	90
NO_3^- -N	1.68	2.88 a	2.24 a	2.01 a	9.76 b
pH	8.11	8.16	8.22	8.08	8.10
Orthophosphate	0.54 a	1.07 b	1.21 b	1.34 b	1.20 b
$\text{SO}_4^{=}$	80.50 a	99.11 a	100.70 ab	112.60 b	135.30 b
Cl^-	30.65 a	35.56 a	41.35 a	44.10 a	78.10 b
Ag	0.002	0.002	0.003	0.002	0.003
Al	5.60 a	2.78 b	4.10 ab	2.60 b	2.00 b
As	<0.05	<0.05	<0.05	<0.05	<0.05
Ba	0.15	0.16	0.12	0.20	0.31
Be	<0.001	<0.001	<0.001	<0.001	<0.001
Ca	24.80 a	26.56 a	24.15 a	34.10 b	50.10 c
Cd	0.001	0.002	0.002	0.001	0.001
Cr	0.04 ab	0.04 ab	0.05 a	0.02 b	0.02 b
Cu	0.01	0.027	0.03	0.05	0.07
Fe	3.10	1.78	2.80	1.90	1.70
K	5.50 a	5.00 a	6.50 ab	9.50 b	14.00 c
Mg	7.57 a	8.30 a	8.13 a	10.45 a	22.00 b
Mn	0.21 a	0.11 b	0.15 ab	0.13 ab	0.07 b
Mo	0.01	0.02	0.02	0.01	0.02
Na	163.00 a	178.89 a	193.00 a	179.00 a	253.50 b
Ni	0.01	0.02	0.03	0.01	0.03
Pb	<0.05	<0.05	<0.05	<0.05	<0.05
Sr	0.27 a	0.31 a	0.28 a	0.39 a	0.85 b
V	0.03	0.03	0.03	0.03	0.03
Zn	0.37	0.41	0.37	0.39	0.35

Different letters indicate differences ($P < 0.05$) between biosolid rates for a given variable. Means of variables that are not followed by letters were not significantly affected by biosolid application.

regulation (SDWR) limit (Table 5). The Cl^- concentration was higher in the 90 Mg ha^{-1} level than in the other biosolid levels, but like $\text{SO}_4^{=}$, all the concentrations were below the SDWR.

As in the Armesa soil, the concentrations of As and Be in the Stellar soil's leachate were lower than the detection limits and the actual concentrations are uncertain. The concentration of Al was, in general, higher in the control than in the biosolid treatments and all concentrations were higher than the SDWR limit. The Ca concentration was not affected by biosolid applications up to 18 Mg ha^{-1} . However, biosolid applications of 34 and 90 Mg ha^{-1} produced higher Ca concentrations than the control. The Cr concentration was higher at lower biosolids rates (0 to 18 Mg ha^{-1}) than at higher biosolids rates (34 and 90 Mg ha^{-1}), but the Cr concentrations were always lower than the MCL.

The concentrations of K tended to increase as the biosolid levels increased. In contrast, the concentration of Mn tended to decrease as biosolid levels increased.

However, all Mn concentrations were higher than the SDWR limit. The concentrations of Mg, Na, and Sr were not affected by biosolid applications up to 34 Mg ha⁻¹, but were highly increased by application of 90 Mg ha⁻¹. Biosolid treatments did not affect the Fe concentration, but all results were higher than the SDWR limit.

Discussion

The leachate NO₃⁻-N concentrations obtained in the Armesa soil were much higher than those in the Stellar soil due to the differences in soil texture. Sandy soils such as the Armesa, with higher hydraulic conductivity, have more possibilities of NO₃⁻-N leaching because NO₃⁻-N is highly soluble (Gaines and Gaines, 1994; Evanylo, 2003). Leaching of NO₃⁻-N beyond the MCL in the Armesa soil was due to the high amount of water applied and to the coarse texture of the soil, but was unrelated to the application of biosolids. Recently, there have been reports of large reservoirs of N, unrelated to human activities, in the subsoil (deeper than 1 m) of several arid regions (Walvoord et al., 2003). Apparently, NO₃⁻-N has been naturally accumulating through centuries in the subsoil of these areas from leaching caused by occasional heavy rains. Our results support the possibility that significant amounts of N can be leached in arid soils of coarse texture if a deep wetting event occurs. However, heavy precipitation events that can drive water deeper than 1 m into the soil profile occur very rarely in the Chihuahuan Desert, perhaps once every 100 years (Reynolds et al., 2000). Nevertheless, our results also indicate that the application of biosolids in the Armesa soil is not likely to magnify N leaching beyond the levels expected under untreated soils.

In comparison to the Armesa soil, the Stellar soil leached less NO₃⁻-N, due to its finer texture and lower hydraulic conductivity (Evanylo, 2003). The higher organic matter content of the Stellar soil likely contributed also to the higher retention and lower leaching of NO₃⁻-N. According to Gaines and Gaines (1994), although NO₃⁻-N is an anion that can readily leach, soils with higher silt, clay, and organic matter retain more NO₃⁻-N, than soils with lower silt, clay, and organic matter. However, the highest biosolids level produced leachate NO₃⁻-N concentrations similar to the MCL. Therefore, although the possibility of NO₃⁻-N leaching is reduced in soils with finer texture, the application of 90 Mg ha⁻¹ of biosolids enhances such a possibility.

The leachate NO₃⁻-N concentrations in our study were lower than those observed in many agricultural systems (Casey et al., 2002) where irrigation can accelerate N leaching. In our study, the amount of water applied was only enough to provide about 1 liter of leachate, after which water application ceased. Therefore, the NO₃⁻-N amounts obtained in our leaching represent a small fraction of the potential amount of NO₃⁻-N present in the soils. The conditions of our study would simulate a large rainfall event that could produce leachate, but in a limited amount. This is important to point out because the concentrations of solutes in the leachate would be a function of the leaching fraction and volume.

Leachate orthophosphate concentrations were higher and more affected by biosolids in the Stellar soil than in the Armesa soil. The orthophosphate group includes several forms of inorganic P that are soluble and susceptible to leaching. However, losses of P by leaching are typically considered minimal because most forms of P are strongly bound by the soil and the soluble forms usually constitute less than 1% of the total soil P (Pierzynski, 1991). However, orthophosphate leaching can be

significant in free-draining, coarse soils (Toor et al., 2005), or in fine textured soil with preferential paths (Jensen et al., 1998). The observations that leachate orthophosphate concentrations were higher in 1) the finer textured soil than in the coarser textured soil, and 2) the biosolid-applied soils than in the control suggest that leaching in the finer Stellar soil was favored by the flow of water carrying biosolid particles through preferential paths caused by cracking. Cracking and swelling are common in soils with relatively higher clay content such as the Stellar as a result of moisture changes. The movement of orthophosphate from soil surface to subsurface horizons represents a loss in the fertilizing potential of biosolids, but it does not represent an adverse effect on drinking water quality. In fact, orthophosphate is added as a corrosion inhibitor in potable water systems at levels of 3.3 mg l^{-1} (Lytle et al., 1996), well above the levels determined in this study.

The water used for the leachate had 1.8 mg l^{-1} of NO_3^- -N and 0.2 mg l^{-1} of orthophosphate and it is not possible with our evaluations to know if the water contributed to the amounts recorded in the leachate. However, the same water was used for all treatments and for both soils and therefore the differences that were found are valid.

The application of 90 Mg ha^{-1} of biosolids represented a significantly higher potential for leaching of several elements and compounds (NO_3^- -N, $\text{SO}_4^{=}$, Cl^- , Ca, K, Mg, Na, and Sr) than lower application rates. In line with this, previous reports (Sommers et al., 1979; Fresquez et al., 1990; Wester et al., 2003) have argued against the application of 90 Mg ha^{-1} of biosolids for the potential accumulation of undesirable elements and substances in soil. Although higher plant production has been achieved with this high application rate (Mata-Gonzalez et al., 2004), the potential leaching risks do not seem to justify the production benefits.

Of the metals regulated by USEPA, Cd, Ba, and Cr were found in lower leachate concentrations than the MCL regardless of soil type or biosolid application rate. Similarly, the concentration of Be was lower than the detection limit (0.001 mg l^{-1}) indicating that the actual concentration was below the MCL (0.004 mg l^{-1}). These results suggest that, for these metals, the quality of the leachate is not negatively affected by the application of biosolids, which is in agreement with previous reports (Sommers et al., 1979; Emmerich et al., 1982). A factor that perhaps contributed to the minimal effect of biosolids on metal leaching was that pH levels remained high despite the biosolid application. Similarly, Keller et al. (2002) also reported no effect of biosolids on Cd leachate concentration and only minimal effects on Cr with no acidification of the leachate. In contrast, McLaren et al. (2004) reported that biosolid application increased the Cd concentrations in the leachate concomitantly with a decrease in pH.

Cu and Pb are metals for which USEPA has action levels, but not MCL-established. For Cu, the concentrations determined were lower than the action level irrespective of soil types or biosolids application. For Pb, the concentrations determined were lower than the detection limit (0.05 mg l^{-1}) in both soils, but it is uncertain how the actual concentrations of this element were in comparison to the action level (0.015 mg l^{-1}).

In the Stellar soil, the concentrations of Al and Mn were higher than the SDWR, irrespective of biosolids levels. In contrast, these two elements had much lower concentrations in the Armesa soil. Therefore, the intrinsic chemical characteristics of the Stellar soil, and not the biosolids applied, were responsible for the high concentrations of Al and Mn in the leachate. Biosolids, in fact, seemingly lowered the amount

of Al and Mn that leached, perhaps due to the adsorption capacity of the organic matter. It has been reported that organic matter can bind Al and Mn in soil surfaces and reduce their mobility (Kabata-Pendias and Pendias, 1992)

Conclusions

We hypothesized that the application of biosolids would increase the concentration of elements and compounds in the leachate and negatively affect its water quality. In general this was not supported by the results. Biosolids did not increase NO_3^- -N leaching with respect to the control, except when they were applied at 90 Mg ha^{-1} in the Stellar soil. In the Armesa soil, the leachate NO_3^- -N concentrations were higher than the MCL, but this was the same for the control and biosolid treatments. Orthophosphate leaching occurred mainly in the Stellar soil and was favored by biosolid application, but the levels obtained in the leachate do not represent a threat to drinking water characteristics. The concentrations of the trace elements Cd, Ba, Cr, and Be, which are regulated by USEPA, were below the MCL for drinking water irrespective of biosolid treatment or soil type. The application of 90 Mg ha^{-1} of biosolids represented a significantly higher potential of leaching for many elements and compounds (NO_3^- -N, $\text{SO}_4^{=}$, Cl^- , Ca, K, Mg, Na, and Sr) than applications of 34 Mg ha^{-1} or lower. In general, the application of biosolids up to 34 Mg ha^{-1} does not pose adverse effects for subsurface water quality.

This study was conducted under extremely conservative assumptions and the results should be understood in that context. For example, in order to obtain leachate we applied 20% to 35% of the average annual precipitation in a single day without run-off. Clearly, this departs from normal conditions. In areas similar to our study area, precipitation conducive to leaching may occur once every 100 years (Reynolds et al., 2000). Therefore, the application of biosolids under the climatic conditions of areas such as the Chihuahuan Desert is safe in terms of subsurface water quality. In addition, groundwater sources of the study area, which can be used for drinking water, are located at 50 m or more and it is difficult to visualize leaching to contaminate to that depth. On the other hand, this study only tested a single application of biosolids and the results under multiple applications deserve further investigation.

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