
May 2010 Volume 91 Number 5 ISSN 0301-4797
ELSEVIER
Journal of
Environmental
Management

Journal of Environmental Management 91 (2010) 1123–1130

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Infrequent composted biosolids applications affect semi-arid grassland soils and vegetation

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A R T I C L E I N F O

Article history:
Received 5 May 2009
Received in revised form
11 December 2009
Accepted 3 January 2010
Available online 25 January 2010

Keywords:
Composted biosolids application
Long-term effects
Metals
Nitrogen
Phosphorus
Plant species composition
Short-term effects
Soil carbon

A B S T R A C T

Monitoring of repeated composted biosolids applications is necessary for improving beneficial reuse program management strategies, because materials will likely be reapplied to the same site at a future point in time. A field trial evaluated a single and a repeated composted biosolids application in terms of long-term (13–14 years) and short-term (2–3 years) effects, respectively, on soil chemistry and plant community in a Colorado semi-arid grassland. Six composted biosolids rates (0, 2.5, 5, 10, 21, 30 Mg ha^{-1}) were surface applied in a split-plot design study with treatment (increasing compost rates) as the main factor and co-application time (1991, or 1991 and 2002) as the split factor applications. Short- and long-term treatment effects were evident in 2004 and 2005 for soil 0–8 cm depth pH, EC, NO_3-N, NH_4-N, total N, and AB-DTPA soil Cd, Cu, Mo, Zn, P, and Ba. Soil organic matter increases were still evident 13 and 14 years following composted biosolids application. The repeated composted biosolids application increased soil NO_3-N and NH_4-N and decreased AB-DTPA extractable Ba as compared to the single composted biosolids application in 2004; differences between short- and long-term applications were less evident in 2005. Increasing biosolids rates resulted in increased native perennial grass cover in 2005. Plant tissue Cu, Mo, Zn, and P concentrations increased, while Ba content decreased depending on specific plant species and year. Overall, the lack of many significant negative effects suggests that short- or long-term composted biosolids application at the rates studied did not adversely affect this semi-arid grassland ecosystem.

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1. Introduction

Biosolids land application is a major method of disposal in the US, with approximately 50% land applied nowadays (US EPA, 2007a). In U.S. Environmental Protection Agency (US EPA) Region 8, which encompasses Colorado, Wyoming, Utah, Montana, North and South Dakota, 85% of biosolids are land applied (US EPA, 2007b). Biosolids or composted biosolids land application appears to offer a solution to the disposal of this resource (Speir et al., 2004) by recycling plant nutrients in an environmentally sound manner. Composting is recognized to sanitize and stabilize biosolids (US EPA, 1995), creating a product that results in the transformation of organic compounds to a higher fraction of humic and fulvic acids which can contribute to reduced metal bioaccessibility (Brown et al., 2003). Thus, composting biosolids makes for a more attractive product for handling and use. The use of composted biosolids in research settings is extensive.

Zubillaga and Lavado (2002) studied the effects of composted biosolids on lettuce (*Lactuca sativa* var. capitata). The authors observed an increase of up to 40% in biomass production, an inverse relationship with Zn leaf content, and a positive relationship in Cu and Ni plant concentrations with increasing composted biosolids application rate. Mantovi et al. (2005) applied composted, dewatered, and liquid biosolids at rates of 5 and 10 Mg ha^{-1} yr^{-1} over a 12-year period to a winter wheat (*Triticum aestivum* L.)–sugar beet (*Beta vulgaris* L.)–maize (*Zea mays* L.) rotation. The authors noted an increase in topsoil organic matter content with composted biosolids application as compared to dewatered or liquid biosolids, and as compared to N fertilizer, the composted biosolids increased wheat grain N, P, Zn, and Cu, sugar beet N and Cu, and corn Cu. Composted biosolids application has also been shown to positively affected barley (*Hordeum vulgare*) and Chinese cabbage (*Brassica rapa* sp.) yield, but resulted in increased soil and crop Cu and Zn concentrations (Wei and Liu, 2005). de Andres et al. (2007)

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0301-4797/$ – see front matter Published by Elsevier Ltd.
doi:10.1016/j.jenvman.2010.01.004

Table 1
Fort Collins, CO Meadow Springs Ranch background soil, 1991 and 2002 composted biosolids analysis, and US EPA 40 CFR Part 503 Table 3 metal limits. All values are expressed on a dry weight basis.

Property	Background soil	1991 Composted biosolids	2002 Composted biosolids	US EPA 40 CFR Part 503 Table 3 limits[b]
Total solids (%)	ND[a]	57.8	58.0	NA[c]
pH	5.5	5.0	6.0	NA
EC (dS m^{-1})	0.2	15.3	ND	NA
Organic N (mg kg^{-1})	1545	20,900	25,400	NA
NO_3-N (mg kg^{-1})	1.2	2541	3492	NA
NH_4-N (mg kg^{-1})	3.9	3000	1800	NA
P (mg kg^{-1})	353	14,900	34,700	NA
Fe (mg kg^{-1})	10,030	9968	ND	NA
Cd (mg kg^{-1})	0.7	3.7	2.6	39
Cr (mg kg^{-1})	12	73.1	21.4	1200
Cu (mg kg^{-1})	9.6	590	474	1500
Mo (mg kg^{-1})	0.1	11.5	19.0	NA
Ni (mg kg^{-1})	7	28.6	16.7	420
Pb (mg kg^{-1})	8.6	122	39.0	300
Zn (mg kg^{-1})	37	802	652	2800
Ba (mg kg^{-1})	163	454	29.0	NA

[a] ND = not determined.
[b] US EPA (1993).
[c] NA = not applicable.

applied 0 and 40 Mg ha^{-1} of composted biosolids to an abandoned alkaline (pH 8.5) soil low in organic matter (9.6 g kg^{-1}) and monitored shrub survival and growth. Composted biosolids increased shrub growth and biomass production, although it slightly reduced shrub survival. Increased shrub growth was related to an increase in soil fertility status (i.e. increased NO_3-N and extractable P; reduction in pH), yet this may also have been responsible for reduction in species survivability as competition for water increased. Tarrason et al. (2007) applied 10 Mg ha^{-1} of composted biosolids to an unproductive shrub land, showing that vegetative cover, herbaceous biomass, and annual tree growth increased as compared to a control.

To our knowledge, only one research group has studied composted biosolids land application to semi-arid rangelands as a means of both a disposal and fertilization practice. Harris-Pierce et al. (1993) and Harris-Pierce (1994) studied the effects of increasing composted biosolids application to a shortgrass steppe community in Colorado. Composted biosolids were applied at rates up to 30 Mg ha^{-1}. Within several years following application the plant canopy cover increased, yet total aboveground biomass was unchanged with increasing composted biosolids application; observed changes were species specific. Plant N, P, K, Cu, Zn, and Ni concentrations generally increased with increasing application rate. Plant Mo tended to decrease possibly due to greater species specific plant growth causing a dilution effect. Soil organic matter, inorganic N, and total P, Cu, Zn, Pb, Cd, and Mo increased in the surface soil layer as composted biosolids application rates increased.

Although these composted biosolids studies support the concept of beneficial reuse, the long-term benefits of the composted biosolids applications were not researched. Long-term studies on soils, plant diversity and productivity are necessary to accurately assess the lasting environmental impacts of recycling these materials on rangeland ecosystem stability. In addition, a second issue of

Table 2
Effect of increasing composted biosolids application on long-term (single application, 1991) and short-term (repeated application, 2002) soil pH, EC (dS m^{-1}), NO_3-N (mg kg^{-1}), NH_4-N (mg kg^{-1}), total C (%), and total N (%) in the 0–8 cm depth at the Meadow Springs Ranch semi-arid rangeland site, 2004 and 2005. Values inside parentheses represent 1 standard error of the mean. Trt corresponds to treatment (i.e. composted biosolids application rate).

Year; property	Long-term/short-term	Composted biosolids application rate (mg ha^{-1})						Trt effect LSD	Time effect LSD	Trt × time interaction
		0	2.5	5	10	21	30			
2004										
pH	Long-term	6.0 (0.4)	6.4 (0.5)	6.0 (0.2)	6.4 (0.5)	5.6 (0.2)	5.6 (0.3)	0.4*	NS	NS
	Short-term	6.3 (0.1)	6.2 (0.4)	6.0 (0.7)	5.8 (0.3)	5.6 (0.5)	5.3 (0.2)			
EC	Long-term	0.16 (0.06)	0.22 (0.11)	0.18 (0.05)	0.41 (0.19)	0.30 (0.11)	0.26 (0.04)	0.15*	NS	NS
	Short-term	0.18 (0.07)	0.27 (0.12)	0.30 (0.13)	0.34 (0.15)	0.41 (0.16)	0.54 (0.18)			
NO_3-N	Long-term	3.6 (1.4)	4.3 (0.6)	3.3 (1.7)	7.2 (3.1)	11.0 (7.6)	8.5 (2.0)	5.5*	4.0*	NS
	Short-term	3.5 (1.9)	5.7 (3.7)	6.4 (5.3)	11.9 (6.7)	14.4 (4.6)	24.7 (11.3)			
NH_4-N	Long-term	3.1 (0.7)	4.8 (3.9)	4.2 (1.0)	7.4 (4.5)	6.3 (2.6)	9.5 (2.1)	1.2*	4.0*	NS
	Short-term	4.1 (1.0)	6.0 (4.2)	6.8 (5.0)	15.4 (8.0)	12.4 (4.9)	15.5 (5.3)			
Total C	Long-term	1.56 (0.53)	1.35 (0.26)	1.81 (0.21)	1.85 (0.67)	2.15 (0.47)	2.51 (0.90)	0.53*	NS	NS
	Short-term	1.62 (0.05)	1.59 (0.18)	2.28 (0.34)	1.97 (0.17)	2.35 (0.41)	2.95 (0.82)			
Total N	Long-term	0.11 (0.06)	0.08 (0.04)	0.12 (0.03)	0.11 (0.05)	0.14 (0.04)	0.19 (0.10)	0.06*	NS	NS
	Short-term	0.11 (0.01)	0.10 (0.03)	0.15 (0.04)	0.13 (0.02)	0.18 (0.05)	0.23 (0.08)			
2005										
pH	Long-term	5.7 (0.3)	6.0 (0.2)	5.8 (0.1)	5.7 (0.2)	5.5 (0.2)	5.4 (0.1)			*
	Short-term	5.9 (0.2)	5.9 (0.2)	6.1 (0.5)	5.6 (0.2)	5.9 (0.5)	5.4 (0.1)			
EC	Long-term	0.30 (0.16)	0.36 (0.12)	0.28 (0.17)	0.24 (0.07)	0.22 (0.08)	0.24 (0.10)	NS	NS	NS
	Short-term	0.24 (0.07)	0.34 (0.07)	0.37 (0.22)	0.25 (0.04)	0.44 (0.18)	0.25 (0.03)			
NO_3-N	Long-term	0.7 (0.5)	0.6 (0.4)	0.9 (0.6)	5.3 (7.1)	2.9 (3.4)	6.4 (8.4)	NS	NS	NS
	Short-term	0.8 (0.5)	1.6 (1.6)	1.6 (0.4)	5.2 (4.8)	22.0 (37.0)	3.0 (1.5)			
NH_4-N	Long-term	1.9 (0.3)	2.3 (0.8)	3.6 (0.9)	9.3 (11.0)	7.0 (2.8)	7.2 (5.8)	5.1*	NS	NS
	Short-term	2.3 (0.5)	4.3 (2.3)	5.1 (2.0)	11.9 (11.7)	11.1 (8.9)	12.1 (3.4)			
Total C	Long-term	1.53 (0.58)	1.66 (0.18)	1.87 (0.34)	2.11 (0.63)	2.48 (0.35)	2.63 (0.35)	0.53*	NS	NS
	Short-term	1.63 (0.32)	1.89 (0.60)	2.05 (0.24)	2.07 (0.50)	2.77 (0.62)	3.58 (0.66)			
Total N	Long-term	0.14 (0.05)	0.15 (0.01)	0.16 (0.02)	0.18 (0.04)	0.22 (0.03)	0.22 (0.03)	0.04*	NS	NS
	Short-term	0.16 (0.03)	0.16 (0.01)	0.18 (0.02)	0.18 (0.03)	0.24 (0.05)	0.31 (0.05)			

*Significance at 5% probability level, NS = not significant.

Table 3
Effect of increasing composted biosolids application on long-term (single application, 1991) and short-term (repeated application, 2002) soil AB-DTPA extractable Cd, Cu, Mo, Zn, P, and Ba concentrations in the 0–8 cm depth at the Meadow Springs Ranch semi-arid rangeland site, 2004 and 2005. Values inside parentheses represent 1 standard error of the mean. Trt corresponds to treatment (i.e. composted biosolids application rate).

Year; property	Long-term/short-term	Composted biosolids application rate (mg ha^{-1})						Trt effect LSD	Time effect LSD	Trt × time interaction
		0 (mg kg^{-1})	2.5 (mg kg^{-1})	5 (mg kg^{-1})	10 (mg kg^{-1})	21 (mg kg^{-1})	30 (mg kg^{-1})			
2004										
Cd	Long-term	0.08 (0.02)	0.07 (0.01)	0.07 (0.01)	0.10 (0.02)	0.12 (0.03)	0.13 (0.01)	0.02*	NS	NS
	Short-term	0.07 (0.02)	0.07 (0.02)	0.09 (0.03)	0.11 (0.01)	0.12 (0.01)	0.18 (0.05)			
Cu	Long-term	1.10 (0.22)	1.32 (0.31)	1.31 (0.19)	3.32 (1.04)	3.44 (0.95)	4.56 (1.64)	1.21*	NS	NS
	Short-term	0.94 (0.26)	1.48 (0.52)	2.16 (0.91)	3.34 (0.97)	3.73 (0.33)	6.74 (2.56)			
Mo	Long-term	0.016 (0.009)	0.020 (0.004)	0.027 (0.020)	0.071 (0.037)	0.100 (0.021)	0.136 (0.065)			*
	Short-term	0.012 (0.003)	0.034 (0.014)	0.071 (0.074)	0.110 (0.032)	0.171 (0.034)	0.385 (0.140)			
Zn	Long-term	0.87 (0.25)	1.26 (0.44)	1.40 (0.35)	5.77 (2.03)	6.58 (2.21)	8.54 (3.32)	2.35*	NS	NS
	Short-term	0.69 (0.14)	1.71 (0.98)	3.41 (2.14)	5.94 (1.79)	7.16 (0.58)	13.1 (4.70)			
P	Long-term	19 (7)	21 (7)	21 (4)	47 (9)	51 (10)	62 (17)			*
	Short-term	14 (3)	26 (6)	34 (15)	53 (12)	70 (4)	114 (20)			
Ba	Long-term	3.93 (0.61)	2.64 (1.22)	2.69 (1.37)	1.99 (0.82)	1.39 (0.38)	1.49 (1.16)	0.86*	0.44*	NS
	Short-term	3.64 (0.40)	2.57 (0.37)	1.70 (0.36)	1.19 (0.49)	0.66 (0.24)	0.20 (0.16)			
2005										
Cd	Long-term	0.13 (0.04)	0.12 (0.03)	0.17 (0.04)	0.21 (0.07)	0.21 (0.03)	0.28 (0.07)	0.05*	NS	NS
	Short-term	0.11 (0.03)	0.15 (0.04)	0.18 (0.05)	0.21 (0.04)	0.22 (0.04)	0.34 (0.09)			
Cu	Long-term	1.76 (0.28)	2.33 (0.41)	3.36 (0.70)	6.56 (1.78)	7.19 (1.64)	10.0 (3.66)	2.46*	NS	NS
	Short-term	1.77 (0.33)	3.30 (1.37)	4.29 (0.90)	6.62 (1.68)	8.47 (1.52)	15.1 (6.42)			
Mo	Long-term	0.023 (0.006)	0.030 (0.016)	0.042 (0.017)	0.123 (0.025)	0.173 (0.047)	0.229 (0.109)			*
	Short-term	0.017 (0.007)	0.070 (0.039)	0.148 (0.025)	0.236 (0.077)	0.386 (0.161)	0.841 (0.301)			
Zn	Long-term	1.45 (0.29)	2.04 (0.82)	3.71 (1.53)	10.2 (3.77)	11.4 (2.67)	16.0 (5.78)	3.88*	NS	NS
	Short-term	1.25 (0.36)	3.95 (2.07)	6.12 (1.31)	9.95 (3.31)	13.8 (3.18)	23.8 (8.69)			
P	Long-term	18 (6)	17 (6)	26 (7)	46 (14)	49 (12)	61 (12)			*
	Short-term	13 (3)	27 (12)	33 (7)	51 (10)	67 (9)	104 (27)			
Ba	Long-term	3.31 (0.36)	3.12 (0.65)	3.07 (0.20)	2.29 (0.25)	2.22 (0.18)	2.00 (0.50)			*
	Short-term	3.50 (0.47)	2.66 (0.60)	1.91 (0.50)	2.33 (0.46)	1.31 (0.39)	1.15 (0.34)			

*Significance at 5% probability level, NS = not significant.

practical importance is the subsequent impact on semi-arid rangeland ecosystems following repeated composted biosolids applications. For a beneficial reuse program to be successful, it would be ideal if materials could be reapplied to the same site over time without causing any detrimental effects to soils or vegetation. Therefore, we utilized the Harris-Pierce et al. (1993) research location with the objective to quantify the long-term effects of a single composted biosolids application and short-term effects of a repeated composted biosolids application on soil chemical properties, plant species composition, and plant nutrient and metal concentrations in a semi-arid rangeland ecosystem.

2. Materials and methods

2.1. Experimental design, site characteristics, and composted biosolids analyses

In August 1991, 15 × 15 m test plots were established at the 10,500 ha Meadow Springs Ranch (40°53′46″N, 104°52′28″W) owned by the city of Fort Collins, Colorado, USA. Treatments consisted of 0, 2.5, 5, 10, 21 and 30 Mg (dry weight) composted biosolids ha^{-1} surface applied with no incorporation. Composted biosolids were applied with a side-discharge spreader and all treatments were replicated four times in a randomized complete block design. In October 2002 the original plots were split in half. One-half received a second surface (no incorporation) application using the same treatments at the original rates. This resulted in a split-plot block design with rate as the main factor and co-application time (1991 and 2002) as the split factor. Long-term and short-term plots are defined as those which received composted biosolids either once in 1991 or twice, both in 1991 and 2002. All plots used in this study were fenced to 2 m in height to exclude grazing by domestic livestock, but native antelope were regular visitors of the study plots as their feces were routinely observed within the fenced area.

Composted biosolids were obtained from the city of Fort Collins, Colorado wastewater treatment facility. Composted biosolids elemental composition (Table 1) was determined by $HClO_4$–HNO_3–HF–HCl digestion (Soltanpour et al., 1996) followed by analysis using inductively coupled plasma-atomic emission spectrometry (ICP-AES). Nitrate-N and NH_4-N were determined following methods outlined by Mulvaney (1996), pH (Thomas, 1996) and electrical conductivity (EC; Rhoades, 1996) were determined by the saturated paste method of Rhoades (1996). Composted biosolids total N content was determined by a concentrated H_2SO_4 digestion (Bremner, 1996) and organic N content via subtraction of inorganic N species from total N. Regulated elemental constituents fell below the EPA 40 CFR Part 503 Table 3 limits (US EPA, 1993).

The cattle-grazed Meadow Springs Ranch is a semi-arid shortgrass steppe rangeland community dominated by perennial grasses, including western wheatgrass (*Pascopyrum smithii* (Rydb.) A. Löve) and needle and thread grass (*Hesperostipa comata*). The research area receives 330–380 mm of mean annual precipitation (NRCS, 1980). The research site soil is classified as an Altvan loam (fine-loamy over sandy or sandy-skeletal, mixed, superactive, Mesic Aridic Argiustoll) with 0–3% slopes. The Altvan series consists of deep, well drained soils that formed in mixed alluvial deposits (NRCS, 1980).

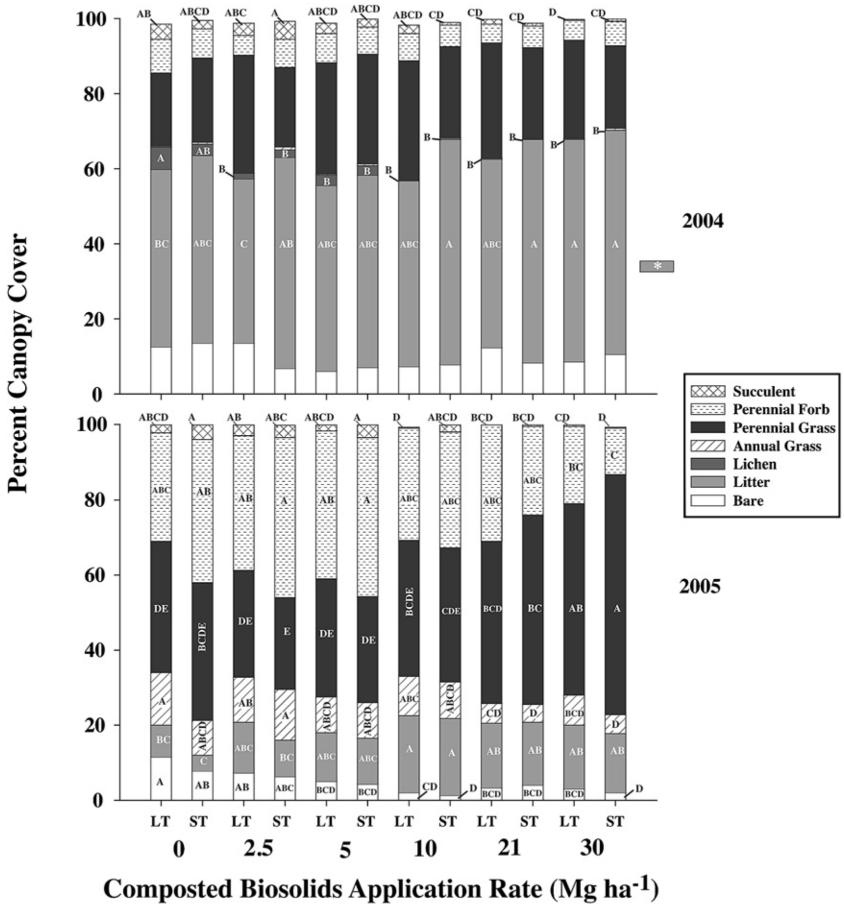

Fig. 1. Percent canopy cover of various major plant life forms and other cover classes from 2004 to 2005 in replicated ($n = 4$) semi-arid grassland plots amended with composted biosolids (0, 2.5, 5, 10, 21, and 30 Mg ha^{-1}). Treatments were applied to plots in either 1991 (LT = long-term – single application) or in 1991 and 2002 (ST = short-term – repeated application). Cover of rock, shrubs, biennial forb and annual forb are not depicted here because they were only a minor component of cover. Capital letters indicate significant differences across composted biosolids application rates and reapplication treatment within a year using a Fisher's LSD test ($\alpha = 0.05$, $n = 4$). Asterisks (*) within a graph panel indicate a significant effect of the 2002 repeated application on the indicated cover class, in this case, litter in 2004 (Fisher's LSD, $\alpha = 0.05$, $n = 12$).

2.2. *Soil chemical characterization*

One composite soil sample, comprised of 3 cores, was obtained from each plot using a mechanical probe to depths of 0–8, 8–15, and 15–30 cm in late June of 2004 and 2005. These depth increments were identical to that collected by Harris-Pierce et al. (1993) in the same research plots. All soils were returned to the laboratory, air-dried, ground to pass a 2-mm sieve, then analyzed for pH and EC using a saturated paste, NO_3-N and NH_4-N using a 2 M KCl extract, and ammonium-bicarbonate diethylenetriaminepentaacetic acid (AB-DTPA; Barbarick and Workman, 1987) extractable Ca, Mg, Na, K, P, Al, Fe, Mn, Cu, Zn, Ni, Mo, Cd, Cr, Sr, B, Ba, and Pb using ICP-AES. Total C and N were also determined on ball-mill ground soil using a LECO-1000 CHN auto-analyzer (Nelson and Sommers, 1996).

2.3. *Plant community characterization and plant tissue chemistry*

During mid-June of 2004 and 2005 aboveground plant canopy percent cover by species was determined in each plot using seven, 15 m transects with measurements obtained every 1.0 m. The number of plant taxa encountered along each transect was used as an estimate of species diversity within plots. In addition, the two dominant plant species (western wheatgrass and needle and thread grass) were harvested from each plot for tissue nutrient analyses. Samples were placed in coolers, transported to the laboratory, ground, weighed and then analyzed for total C and N by LECO-1000 CHN auto-analyzer (Nelson and Sommers, 1996). A subsample was digested in concentrated HNO_3 (Huang and Schulte, 1985) and analyzed for Ca, Mg, Na, K, P, Al, Fe, Mn, Cu, Zn, Ni, Mo, Cd, Cr, Sr, B, Ba, and Pb using ICP-AES.

2.4. *Statistical approach*

Statistical analysis was performed on all soil chemical and plant data using a split-plot in time design in the Proc GLM model, SAS software version 9.1 (SAS Institute, 2002). We tested our hypotheses using an $\alpha = 0.05$, calculated a Fisher's Protected Least Significant Difference (LSD; Steel and Torrie, 1980) when significance was observed within treatments or between timing of application. If a significant interaction existed between treatment and time, significance for the interaction is only presented. Plant community cover data was analyzed using square root transformed data for variables that were not normally distributed.

3. Results

Notable changes in soil chemical characteristics associated with single and repeated composted biosolids application were observed in the 0–8 cm depth; fewer soil chemical characteristic differences were found in the 8–15 and 15–30 cm depths. Therefore, soil results will focus solely on the 0–8 cm depth. In addition, soil AB-DTPA extractable and plant Ca, Mg, Na, K, Al, Fe, Mn, Ni, Cr, Sr, B, and Pb concentrations were unaffected by a single or repeated composted biosolids application, and thus will not be discussed for brevity sake.

3.1. Soil chemical characterization

The 2004 soil 0–8 cm pH, EC, NO_3-N, NH_4-N, total C, and total N were all affected by composted biosolids application; differences in these constituents were less evident in 2005 (Table 2). Soil pH decreased while EC, NO_3-N, NH_4-N, total C, and total N increased with increasing composted biosolids application rates in 2004. Applying a second application of composted biosolids increased soil NO_3-N and NH_4-N content as compared to the single application. In 2005, soil NH_4-N, total C, and total N increased with increasing composted biosolids application rate. Total soil C differences, at composted biosolids rates greater than 21 Mg ha^{-1} as compared to lower rates, were still evident in the long-term (single application) plots in 2004 and 2005.

The AB-DTPA extractable 0–8 cm soil Cd, Cu, Mo, Zn, and P concentrations increased, while Ba concentration decreased in 2004 and 2005 with increasing composted biosolids application rates (Table 3). These increases were expected because both the single and repeated composted biosolids applications added more of these elements to the soil (Table 1).

3.2. Plant community characterization

Single and repeated composted biosolids applications resulted in few effects in plant community composition relative to controls (Fig. 1). During the June 2004 sampling most of the standing vegetation was senescent. Spring 2005 growing conditions were favorable and resulted in greater live vegetation cover, and notably an increase in perennial grasses. Thus, the effects of single and repeated composted biosolids applications on the plant community were more evident in 2005 than in 2004.

3.3. Plant tissue chemistry

Cadmium, Cu, Zn, P, and Ba plant tissue concentrations from the two dominant on-site species, western wheatgrass and needle and thread grass, are presented in Tables 4 and 5. Cadmium content was below detection in both years and Mo content was below detection in 2004 for both species. Single and repeated composted biosolids application did not affect plant Cu concentration in 2004. However, in 2004 western wheatgrass Zn concentration showed a significant treatment by time interactions, and needle and thread grass Zn concentration increased with increasing composted biosolids rate as well as with repeated application. Significant interactions were also present for P and Ba plant concentrations in 2004.

Western wheatgrass Cu, Mo, Zn, and P were affected by a significant treatment by time interaction, while plant Ba content decreased in 2005 with increasing composted biosolids application. Needle and thread grass P concentration increased with increasing and repeated composted biosolids application, while Ba concentrations followed opposite trends.

Table 4
Effect of increasing composted biosolids application on long-term (single application, 1991) and short-term (repeated application, 2002) western wheatgrass (*Pascopyrum smithii* (Rydb.) A. Löve) Cd, Cu, Mo, Zn, P, and Ba concentrations at the Meadow Springs Ranch semi-arid rangeland site, 2004 and 2005. Values inside parentheses represent 1 standard error of the mean. Trt corresponds to treatment (i.e. composted biosolids application rate).

Year; property	Long-term/short-term	Composted biosolids application rate (mg ha^{-1})						Trt effect LSD	Time effect LSD	Trt × time interaction
		0 (mg kg^{-1})	2.5 (mg kg^{-1})	5 (mg kg^{-1})	10 (mg kg^{-1})	21 (mg kg^{-1})	30 (mg kg^{-1})			
2004										
Cd	Long-term	ND[a]	ND	ND	ND	ND	ND			
	Short-term	ND	ND	ND	ND	ND	ND			
Cu	Long-term	3.11 (0.46)	4.32 (2.55)	3.76 (1.48)	2.84 (0.35)	3.75 (0.12)	3.11 (0.62)	NS	NS	NS
	Short-term	3.01 (0.50)	2.93 (0.62)	2.95 (0.22)	3.15 (0.24)	3.57 (0.57)	3.26 (0.52)			
Mo	Long-term	ND	ND	ND	ND	ND	ND			
	Short-term	ND	ND	ND	ND	ND	ND			
Zn	Long-term	11.9 (1.89)	12.0 (1.48)	11.2 (2.05)	11.9 (2.12)	13.8 (2.92)	13.4 (1.01)			*
	Short-term	11.9 (1.33)	10.5 (1.76)	10.9 (1.77)	13.1 (1.57)	17.3 (4.44)	16.5 (1.93)			
P	Long-term	1420 (193)	1500 (176)	1500 (92)	1980 (306)	2370 (379)	2400 (273)			*
	Short-term	1290 (156)	1490 (189)	1750 (350)	2430 (137)	2830 (441)	2940 (303)			
Ba	Long-term	28.5 (8.64)	20.8 (4.16)	22.0 (4.41)	26.2 (5.52)	27.3 (1.85)	28.7 (11.3)			*
	Short-term	23.6 (2.96)	20.7 (5.32)	19.8 (5.20)	19.1 (2.15)	14.7 (2.50)	13.2 (3.62)			
2005										
Cd	Long-term	ND	ND	ND	ND	ND	ND			
	Short-term	ND	ND	ND	ND	ND	ND			
Cu	Long-term	2.75 (0.59)	2.83 (1.06)	2.86 (0.43)	2.61 (0.61)	2.84 (0.30)	2.65 (0.52)			*
	Short-term	2.99 (0.93)	2.61 (0.50)	2.36 (0.25)	2.91 (0.34)	3.58 (0.52)	3.79 (0.53)			
Mo	Long-term	0.185 (0.075)	0.288 (0.141)	0.216 (0.037)	0.570 (0.170)	0.771 (0.538)	0.478 (0.351)			*
	Short-term	0.262 (0.093)	0.239 (0.129)	0.382 (0.300)	0.515 (0.240)	1.178 (0.595)	1.153 (0.528)			
Zn	Long-term	10.4 (0.72)	11.6 (2.21)	11.5 (1.90)	13.4 (1.53)	14.3 (1.47)	15.1 (2.08)			*
	Short-term	10.8 (0.49)	11.5 (1.59)	11.1 (1.55)	15.1 (3.60)	18.0 (1.51)	21.6 (2.56)			
P	Long-term	2060 (220)	2200 (251)	2330 (197)	2880 (219)	2970 (228)	3000 (105)			*
	Short-term	1940 (158)	2340 (74)	2540 (244)	3310 (355)	3960 (162)	3940 (206)			
Ba	Long-term	27.5 (4.03)	20.8 (10.8)	19.8 (3.56)	21.4 (2.68)	17.9 (2.64)	19.6 (4.24)	5.06*	NS	NS
	Short-term	26.1 (2.75)	21.3 (5.82)	19.8 (3.12)	15.5 (2.71)	15.4 (2.37)	15.0 (4.03)			

*Significance at 5% probability level, NS = not significant.

[a] ND = non-detectable.

Table 5
Effect of increasing composted biosolids application on long-term (single application, 1991) and short-term (repeated application, 2002) needle and thread grass (*Hesperostipa comata*) Cd, Cu, Zn, P, and Ba concentrations at the Meadow Springs Ranch semi-arid rangeland site, 2004 and 2005. Values inside parentheses represent 1 standard error of the mean. Trt corresponds to treatment (i.e. composted biosolids application rate).

Year; property	Long-term/short-term	Composted biosolids application rate (mg ha^{-1})						Trt effect LSD	Time effect LSD	Trt × time interaction
		0 (mg kg^{-1})	2.5 (mg kg^{-1})	5 (mg kg^{-1})	10 (mg kg^{-1})	21 (mg kg^{-1})	30 (mg kg^{-1})			
2004										
Cd	Long-term	ND[a]	ND	ND	ND	ND	ND			
	Short-term	ND	ND	ND	ND	ND	ND			
Cu	Long-term	2.96 (0.23)	2.74 (0.45)	2.62 (0.13)	2.54 (0.36)	2.66 (0.23)	2.63 (0.41)	NS	NS	NS
	Short-term	2.80 (0.70)	2.84 (0.32)	2.76 (0.37)	2.84 (0.36)	2.88 (0.31)	2.77 (0.16)			
Mo	Long-term	ND	ND	ND	ND	ND	ND			
	Short-term	ND	ND	ND	ND	ND	ND			
Zn	Long-term	8.04 (1.70)	7.61 (1.02)	7.29 (1.38)	7.07 (1.11)	8.59 (1.15)	7.88 (1.85)	1.17*	0.69*	NS
	Short-term	7.98 (2.53)	7.45 (1.30)	7.41 (0.33)	7.90 (0.96)	10.8 (1.24)	10.0 (1.18)			
P	Long-term	970 (186)	1170 (81)	1070 (188)	1440 (152)	1630 (173)	1530 (300)			*
	Short-term	880 (215)	1170 (144)	1230 (119)	1570 (153)	1880 (226)	1970 (123)			
Ba	Long-term	24.8 (4.09)	26.4 (3.63)	23.6 (2.21)	24.8 (4.84)	24.2 (2.03)	23.8 (4.78)			*
	Short-term	23.8 (1.45)	23.5 (3.28)	19.9 (6.25)	17.7 (6.16)	12.8 (6.20)	13.6 (4.37)			
2005										
Cd	Long-term	ND	ND	ND	ND	ND	ND			
	Short-term	ND	ND	ND	ND	ND	ND			
Cu	Long-term	2.49 (0.28)	2.40 (0.21)	2.77 (0.23)	2.28 (0.33)	1.98 (0.10)	2.05 (0.08)	NS	NS	NS
	Short-term	2.55 (0.27)	2.79 (0.45)	2.26 (0.21)	2.33 (0.16)	3.00 (2.38)	1.77 (0.77)			
Mo	Long-term	0.304 (0.137)	0.419 (0.247)	0.398 (0.132)	0.782 (0.290)	0.694 (0.389)	0.502 (0.128)	NS	NS	NS
	Short-term	0.274 (0.089)	0.439 (0.284)	0.307 (0.119)	0.529 (0.284)	0.588 (0.462)	0.330 (0.176)			
Zn	Long-term	7.36 (0.88)	8.19 (0.86)	8.19 (1.30)	8.54 (1.45)	7.43 (0.88)	7.47 (0.79)	NS	NS	NS
	Short-term	7.64 (0.68)	8.56 (1.14)	6.86 (0.53)	7.69 (0.72)	7.94 (2.73)	10.3 (1.40)			
P	Long-term	1370 (231)	1510 (99)	1680 (225)	1845 (171)	1760 (158)	1790 (138)	175*	50*	NS
	Short-term	1330 (70)	1640 (124)	1660 (53)	1830 (134)	2000 (353)	2160 (292			
Ba	Long-term	19.2 (1.10)	18.9 (1.00)	19.2 (2.84)	19.4 (0.83)	18.0 (1.99)	16.8 (1.42)	1.51*	1.15*	NS
	Short-term	18.0 (1.55)	19.2 (2.37)	17.8 (0.60)	17.5 (2.91)	15.1 (0.70)	13.5 (2.34)			

* Significance at 5% probability level, NS = not significant.

[a] ND = non-detectable.

4. Discussion

4.1. Soil chemical characterization

Soil chemical characterization results were expected because the composted biosolids utilized in both 1991 and 2002 contained NO$_3$-N, NH$_4$-N, organic N, and salts as measured by EC (Table 1). Fresquez et al. (1990a) also observed a decrease in soil pH and an increase in soil N with increasing biosolids rate applied to a semi-arid grassland in New Mexico.

Total C should have been solely associated with increasing soil organic matter and not with inorganic C compounds, given the slightly acidic inherent soil pH which indicates low concentrations of carbonates (inorganic carbon). This finding implies that application of composted biosolids at rates equal to or greater than 21 Mg ha^{-1} should improve the soil organic matter status in semi-arid rangeland soils. Other researchers have found similar results. Mantovi et al. (2005) applied composted biosolids at 10 Mg ha^{-1} yr^{-1} over a 12-year period to a winter wheat–sugar beet–corn rotation, noting an increase in topsoil organic matter content from $\sim$1.8% to 2.3% as compared to control soils. Fernandez et al. (2007) incubated a composted biosolids amended arid soil and found that C mineralization patterns were similar to control soils. This suggested that composted biosolids C compounds are not as easily degradable by microorganisms as other more labile C sources, and thus would be efficient at increasing total organic C in arid soils. Composting biosolids results in the transformation of organic compounds to a higher fraction of humic and fulvic acids (Brown et al., 2003) which are more resistant to degradation by microorganisms.

Increases in AB-DTPA extractable elements were expected because both the single and repeated composted biosolids applications added these elements to the soil. The decrease in extractable Ba content was due to the precipitation of slightly insoluble BaSO$_4$ not extracted easily by AB-DTPA (Ippolito and Barbarick, 2006). Soil Ba precipitates can lead to less of an environmental concern with regards to Ba transport to surface and ground waters (Ippolito and Barbarick, 2006). In a field trial, Baldwin and Shelton (1999) applied up to 100 Mg ha^{-1} of composted materials including biosolids to burley tobacco (*Nicotiana tabacum* L.). They noted that DTPA-extractable Cd, Cu, and Zn concentrations increased with increasing soil pH, and composts containing greater metal concentrations were associated with greater DTPA soil metal extractability. In a greenhouse study, Moral et al. (2002) applied up to 50 g kg^{-1} of biosolids or composted biosolids and incubated the amended soils for up to 150 days. The authors noted an increase in AB-DTPA extractable Fe, Cu, Mn and Zn, and although both types of biosolids contained similar metal concentrations, metal availability appeared lower in composted biosolids treatments. Composting appeared to promote a stronger association between metal and organic constituents within the composted biosolids (Moral et al., 2002).

4.2. Plant community characterization

During the June 2004 sampling most of the standing vegetation was senescent, reflective of the dry conditions during the spring of

2004. At the end of May 2004 the annual cumulative precipitation was 125 mm (NOAA, 2009), which was a −50 mm departure from normal. Temperature for the month of May 2004 was 2.0 °C above normal (NOAA, 2009). Overall, there was a significant positive effect of composted biosolids on litter cover in 2004 in both single application ($P = 0.026$) and repeated application ($P = 0.003$) plots, likely due to increased production in amended plots in previous years. The increased litter cover was concomitant with reduced cover of lichens ($P = 0.004$) and succulents ($P = 0.007$) in 2004 (Fig. 1).

The most notable effect in 2005 was an increase in perennial grass cover on plots receiving greater rates of composted biosolids (Fig. 1), and was associated with reduced cover in other life forms such as perennial forbs and annual grasses. Others have found similar results with biosolids land application to semi-arid grasslands (Fresquez et al., 1990a, 1990b). The stimulation of perennial grass growth by composted biosolids resulted in a slight reduction in plant species diversity (i.e. number of plant taxa encountered) in single and repeated application plots in 2005 ($P = 0.025$, data not shown). Since the study plots were fenced to exclude grazing by domestic livestock, reduction of the grass canopy under modest levels of livestock grazing might lead to different results than were observed here. There was also less cover of invasive plant species in the highest application rates ($P = 0.0007$; data not shown), which is contrary to what is often observed for nutrient addition studies in this region (e.g. Paschke et al., 2000). Another study at this same site demonstrated increases in native perennial grass growth associated with increasing rates of biosolids application (Sullivan et al., 2006).

4.3. Plant tissue chemistry

Increases in plant concentrations, as with most AB-DTPA extractable elements, were expected because the repeated biosolids application added more of these elements to the soil. Decreases in plant Ba content were also expected because Ba was most likely associated with precipitation of slightly insoluble $BaSO_4$ not readily available to plants (Ippolito and Barbarick, 2006). All plant metal concentrations were approximately an order of magnitude lower than those considered hazardous to domestic livestock (National Research Council, 2005).

Increases in plant metal concentrations associated with increasing composted biosolids application have been observed by others. Mantovi et al. (2005) noted that composted biosolids increased wheat grain P, Zn, and Cu, sugar beet N and Cu, and corn Cu. Wei and Liu (2005) applied increasing amounts of composted biosolids, observing an increase in barley and Chinese cabbage leaf Cu and Zn content, and an increase in barley grain Cu and Zn concentrations. Lettuce Cu and Zn content increased and decreased, respectively, when grown in pots with increasing composted biosolids content (Zubillaga and Lavado, 2002). In all cases the plant metal concentrations were below those considered hazardous to domestic livestock (National Research Council, 2005).

5. Conclusions

The 0–8 cm soil EC, NO_3-N, NH_4-N, total N, and AB-DTPA extractable Cd, Cu, Mo, Zn, and P concentrations increased as expected, because composted biosolids add these constituents to soils. Total soil C also increased with increasing composted biosolids rate, and long-term increases were observed at rates greater than 21 Mg ha^{-1}. Because composted biosolids contain organic compounds relatively resistant to microbial degradation, this finding implies that composted biosolids addition at rates equal to or greater than 21 Mg ha^{-1} should improve the long-term soil organic matter status in semi-arid grassland soils.

The use of composted biosolids resulted in increased cover of native perennial grasses. In general, western wheatgrass and needle and thread grass Cu, Mo, Zn, and P concentrations increased with increasing and repeated composted biosolids application. Again, we expected to observe increases because composted biosolids add these constituents to soils and are subsequently taken up by plants. All plant metal concentrations were below those considered hazardous to domestic livestock at all composted biosolids application rates studied.

Documenting prolonged changes in soil and plant chemistry and plant community structure associated with composted biosolids application is necessary to discern prolonged effects of this practice. Monitoring of repeated composted biosolids applications is also necessary for a beneficial reuse program to be successful, because materials will likely be reapplied to the same site over time. Overall, the lack of many significant negative effects suggests that both short- and long-term applications of composted biosolids may not be detrimental to semi-arid grassland sustainability. Reapplying composted biosolids every 11 years, at rates of up to 30 Mg ha^{-1}, to semi-arid grasslands similar to those studied should pose minimal environmental risk.

Acknowledgments

The USDA-ARS and Colorado State University gratefully acknowledges US EPA Region 8 (Grant #CP978001-01) for its financial, technical, and administrative assistance in funding and managing the project through which this information was discovered. We also thank the City of Fort Collins, Colorado for their continued support of this project.

References

de Andres, F., Walter, I., Tenorio, J.L., 2007. Revegetation of abandoned agricultural land amended with biosolids. Science of the Total Environment 378, 81–83.

Baldwin, K.R., Shelton, J.E., 1999. Availability of heavy metals in compost-amended soil. Bioresource Technology 69, 1–14.

Barbarick, K.A., Workman, S.M., 1987. Ammonium bicarbonate-DTPA and DTPA extractions of sludge-amended soils. Journal of Environmental Quality 16, 125–130.

Bremner, J.M., 1996. Nitrogen – total. In: Sparks, D.L. (Ed.), Methods of Soil Analysis, Part 3 – Chemical Methods. Soil Science Society of America, Madison, WI, USA, pp. 1085–1121.

Brown, S., Chaney, R.L., Hallfrisch, J.G., Xue, Q., 2003. Effect of biosolids processing on lead bioavailability in an urban soil. Journal of Environmental Quality 32, 100–108.

Fernandez, J.M., Plaza, C., Hernandez, D., Polo, A., 2007. Carbon mineralization in an arid soil amended with thermally-dried and composted sewage sludges. Geoderma 137, 497–503.

Fresquez, P.R., Francis, R.E., Dennis, G.L., 1990a. Sewage sludge effects on soil and plant quality in a degraded, semiarid grassland. Journal of Environmental Quality 19, 324–329.

Fresquez, P.R., Francis, R.E., Dennis, G.L., 1990b. Soil and vegetation responses to sewage sludge on a degraded semiarid broom snakeweed/blue grama plant community. Journal of Range Management 43, 325–331.

Harris-Pierce, R.L., 1994. The Effect of Sewage Sludge Application on Native Rangeland Soils and Vegetation. MS thesis. Colorado State University, Fort Collins, CO, USA.

Harris-Pierce, R., Barbarick, K.A., Redente, E.F., 1993. Annual Report to the City of Fort Collins, CO: The Effect of Sewage Sludge Application on Native Rangeland Soils and Vegetation, Fort Collins Meadow Springs Ranch. Colorado State University, Fort Collins, CO, USA.

Huang, C.L., Schulte, E.E., 1985. Digestion of plant tissue for analysis by ICP emission spectroscopy. Communications in Soil Science and Plant Analysis 16, 943–958.

Ippolito, J.A., Barbarick, K.A., 2006. Biosolids affect soil Ba in a dryland wheat agroecosystem. Journal of Environmental Quality 35, 2333–2341.

Mantovi, P., Baldoni, G., Toderi, G., 2005. Reuse of liquid, dewatered, and composted sewage sludge on agricultural land: effects of long-term application on soil and crop. Water Research 39, 289–296.

Moral, R., Moreno-Caselles, J., Perez-Murcia, M., Perez-Espinosa, A., 2002. Improving the micronutrient availability in calcareous soils by sewage sludge amendment. Communications in Soil Science and Plant Analysis 33, 3015–3022.

Mulvaney, R.L., 1996. Nitrogen – inorganic forms. In: Sparks, D.L. (Ed.), Methods of Soil Analysis, Part 3 – Chemical Methods. Soil Science Society of America, Madison, WI, USA, pp. 1123–1184.

National Research Council. 2005. Mineral Tolerance of Animals second revised ed. The National Academies Press, Washington, DC, USA.

Nelson, D.W., Sommers, L.E., 1996. Total carbon, organic carbon, and organic matter. In: Sparks, D.L. (Ed.), Methods of Soil Analysis, Part 3 – Chemical Methods. Soil Science Society of America, Madison, WI, USA, pp. 975–977.

NOAA, 2009. Annual Climatological Summary, Station 053005. Available at: http://cdo.ncdc.noaa.gov/ancsum/ACS (verified March 2009).

NRCS, 1980. Soil Survey of Larimer County Area, Colorado. Available at: http://soils.usda.gov/survey/online_surveys/colorado/larimer/Text-Part%201.pdf (verified March 2009).

Paschke, M.W., McLendon, T., Redente, E.F., 2000. Nitrogen availability and old-field succession in a shortgrass steppe. Ecosystems 3, 144–158.

Rhoades, J.D., 1996. Salinity: electrical conductivity and total dissolved solids. In: Sparks, D.L. (Ed.), Methods of Soil Analysis, Part 3 – Chemical Methods. Soil Science Society of America, Madison, WI, USA, pp. 417–435.

SAS Institute, 2002. SAS/STAT User's Guide. Version 9.1. SAS Inst., Cary, NC.

Soltanpour, P.N., Johnson, G.W., Workman, S.M., Jones Jr., J.B., Miller, R.O., 1996. Inductively coupled plasma emission spectrometry and inductively coupled plasma-mass spectrometry. In: Sparks, D.L. (Ed.), Methods of Soil Analysis, Part 3 – Chemical Methods. Soil Science Society of America, Madison, WI, USA, pp. 91–139.

Speir, T.W., Horswell, J., vanSchaik, A.P., McLaren, R.G., Fietje, G., 2004. Composted biosolids enhance fertility of a sandy loam soil under dairy pasture. Biology and Fertility of Soils 40, 349–358.

Steel, R.G.D., Torrie, J.H., 1980. Principles and Procedures of Statistics: A Biometrical Approach, second ed. McGraw-Hill, New York, NY, USA.

Sullivan, T.S., Stromberger, M.E., Paschke, M.W., Ippolito, J.A., 2006. Long-term impacts of infrequent biosolids applications on chemical and microbial properties of a semi-arid rangeland soil. Biology and Fertility of Soils 42, 258–266.

Tarrason, D., Ortiz, O., Alcaniz, J.M., 2007. A multi-criteria evaluation of organic amendments used to transform an unproductive shrubland into a Mediterranean dehesa. Journal of Environmental Management 82, 446–456.

Thomas, G.W., 1996. Soil pH and Soil Acidity. In: Sparks, D.L. (Ed.), Methods of Soil Analysis, Part 3 – Chemical Methods. Soil Science Society of America, Madison, WI, USA, pp. 475–490.

US EPA, 1993. 40 CFR-Part 257 and 503, Standards for the Disposal of Sewage Sludge; Final Rule. US EPA, Washington, DC, USA.

US EPA, 1995. A Guide to the Biosolids Risk Assessments for the EPA Part 503 Rule. United States Environmental Protection Agency. Office of Wastewater Management, Washington, DC, USA.

US EPA, 2007a. Biosolids. Available at: http://www.epa.gov/owm/mtb/biosolids/genqa.htm (verified March 2009).

US EPA, 2007b. Region 8 – Biosolids. Available at: http://www.epa.gov/region08/water/biosolids/index.html (verified March 2009).

Wei, Y., Liu, Y., 2005. Effects of sewage sludge compost application on crops and cropland in a 3-year field study. Chemosphere 59, 1257–1265.

Zubillaga, M.S., Lavado, R.S., 2002. Heavy metal content in lettuce plants grown in biosolids compost. Compost Science and Utilization 10, 363–367.