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Full Length Research Paper

A study of heavy metals regulated and mended with two different kinds of biosolids

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Land application of biosolids has been shown to benefit degraded rangeland; however, soil metal accumulation has been a concern. To date, nine heavy metals found in land applied biosolids are regulated by the United States Environmental Protection Agency. Concern increases when application rates exceed the agronomic rate. The objective of this study was to monitor changes in soil metal accumulation from a one-time biosolids surface application on disturbed rangeland in Western Utah. Two types of biosolids, aerobically digested and lime stabilized, were applied at rates up to twenty times (20x) the estimated agronomic rate. Biosolids were not incorporated into the soil. Levels of heavy metals were recorded at five different soil depths, 0.2, 0.6, 0.9, 1.2 and 1.5 m. The one-time application was evaluated over a two year period. No significant consistent trend between metal concentration, biosolids application rate, biosolids type, year, and soil depth was found. It was concluded that metal concentrations in this study were below the cumulative loading rate from the 40 Code of Federal Regulations (CFR) Part 503 rule. These findings can help alleviate concerns about environmental and health risks due to metal accumulation from biosolids land application.

Key words: Biosolids application, biosolids-amended soil, agronomic rate, cumulative loading rate, metal accumulation.

Abbreviations: **CFR,** Code of Federal Regulations.

INTRODUCTION

Biosolids, which are treated sewage sludge from municipal wastewater treatment plants, can be utilized as soil conditioners (Brown et al., 2003; Glass, 2000; Wallace et al., 2009) and/or a source of low cost soil nutrients - nitrogen (N) and phosphorus (P). As a result of the focus on improving quality of discharged water, significant amounts of biosolids are produced daily within the state of Utah. How these biosolids are managed is an important issue for treatment plants as well as federal and state regulators. Several options are available for biosolids management. Surface disposal is a possible alternative, but political and economic difficulties exist. Municipalities are reluctant to co-dispose biosolids within municipal solid waste landfills and monofills (biosolids only landfills) are likewise difficult to site. Incineration is another possibility, but air quality concerns make it publicly unacceptable. Beneficial use of biosolids through land application represents a technically feasible and socially acceptable option for managing biosolids (McFarland, 2001).

Biosolids are applied at an agronomic rate which is typically based on the crop nitrogen requirement. Land managers would like to apply higher rates to keep costs down, but metals can accumulate in soil and plants when the agronomic rate is exceeded (Meyer et al., 2004). Metal concentration in biosolidsis regulated by the 40 Code of Federal Regulations (CFR) Part 503 rule before land application (McFarland, 2001). Bioavailable forms of metals can be released from mineralization of organic matter in biosolids and may be toxic to crops and soil

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Table 1. Average surface soil background chemistry (n = 3).

Depth (m)	pH	NO_3-N (mg/kg)	NH_4-N (mg/kg)	EC (dS/m)	SAR
0.2	8.1	19.6	12.3	10.0	128.3
0.6	8.2	66.4	23.2	28.5	20.8
0.9	8.0	92.8	6.7	39.0	46.0
1.2	7.8	110.4	7.9	43.6	47.1
1.5	7.8	131.5	8.8	43.4	46.4

EC = Electrical Conductivity.
SAR = Sodium Adsorption Ratio.

soil microbes (Sloan et al., 1997). Cadmium (Cd) and zinc (Zn) from biosolids were found to have the highest plant availability as well as high accumulation coefficients which increased their concentrations in plants in sandy loam soil at pH 6.5 - 7.2 (Davis and Stark, 1980; Sloan et al., 1997). Plant availability of nickel (Ni), copper (Cu), chromium (Cr), and lead (Pb) decreases in the respective order. In addition, plant availability of Cd and Zn is enhanced with added organic matter (Almas and Singh, 2001), but, if biosolids completely decay, it is unlikely metals totally become plant-available (Hurley, 1980). Plant uptake and leaching may occur very rapidly due to organic matter decomposition; phytotoxicity, groundwater contamination, and even metal transfer into the food chain may result (Beckett and Davis, 1978). However, Sloan et al. (1998) suggested that these effects are more likely long-term than short-term since the breakdown of organic matter from biosolids application is very slow.

Solubility and phytoavailability of trace metals may be reduced because of some favorable properties of biosolids (e.g. pH) and significant amounts of sorbents (e.g. organic matter) (Basta el al., 2005). Previous researchers (McCalla et al., 1977 and Sommers et al., 1976) reported biosolids contained up to 50% natural organic matter by weight and up to 50% inorganic mineral forms by weight (e.g. silicates, phosphates, carbonates, iron (Fe), manganese (Mn), and aluminum (Al) oxides). Basta et al., (2005) also stated both sorption capacity and properties of both soil and biosolids would affect metal availability. In a variety of soils, Cu, Pb, Ni, and Zn were reported to be strongly adsorbed (Buchter et al., 1998).

Semi- arid rangeland production was improved by organic matter and trace metal addition from biosolids land application when compared with unamended soil (Fresquez et al., 1991; Pierce et al., 1998). Production and quality of native grass species in Colorado rangelands increased at various biosolids loading rates (Pierce et al., 1998). Despite environmental and economic benefits, questions still remain regarding fate and transport of biosolids constituents, particularly at application rates significantly greater than the agronomic rate. Potential adverse environmental effects have been a special concern to some (McBride, 1995).

The objective of this study was to summarize the findings of heavy metals regulated under the 40 CFR Part 503 rule in soils amended with two different kinds of biosolids at application rates exceeding the agronomic rate.

MATERIALS AND METHODS

Soil sample replicates were taken in September of 2004 to establish soil background chemistry at the rangeland test -plot site. A one-time application of lime stabilized and aerobically digested biosolids were applied with a manure spreader to test plots in December of 2005. Soil samples were taken five months later in May of 2006 and one year later in May of 2007. It was the initial intention to continue annual sampling for up to five years, however, financial limitations allowed the study to go only two years.

Site description

The study site was located on private rangeland in Western Utah. Elevation is 1360 m. Average annual precipitation is 150 - 200 mm, mean annual air temperature 7 - 10°C, and average frost- free period is 120 - 160 days. Permeability is moderately rapid in this soil; available water capacity is moderate at 125 - 165 mm. The water-supplying capacity is 90 - 140 mm. Effective rooting depth is 152 cm or more. The content of organic matter in the surface layer is 0.5 - 1.0%. Runoff is slow, hazard of water erosion slight, and wind erosion moderate (USDA, 2000).

Soil characterization

Soil at the test site is Tooele Series, a coarse- loamy, mixed, superactive, calcareous, mesic Typic Torriorthents. It is found on deep, well-drained lake terraces and fan remains at 0 to 5% slopes. It is formed in eolian material, lacustrine sediments, and alluvium derived from mixed rock sources. Slopes are long and linear or slightly convex. The present vegetation in most areas is black greasewood, shadscale, cheatgrass, gray molly and trident salt - bush (USDA, 2000). Background soil chemistry is given in Table 1.

Biosolids land application

Aerobically digested and lime stabilized biosolids were surface applied on 0.13 ha test plots at one, five, ten and twenty (1, 5, 10 and 20x) times the estimated agronomic rate. Application was made only once at the beginning of the study. Biosolids were not incorporated into the soil. Lime stabilized biosolids were not applied at 20x due to the excessive amount. Individual plots were

Table 2. Concentrations (mg/kg) of control soil surface (0.2 m depth) heavy metals compared to national mean, and study method detection limits (MDL).

Heavy metal	MDL	National mean*	Control 1 soil	Control 2 soil
Arsenic	5.0	7.1	4.8 ± 0.5	NA
Cadmium	1.5	2.7	<**	<
Copper	2.5	558.1	<	9.2 ± 0.7
Lead	2.5	76.6	<	<
Mercury	NA	1.2	NA	NA
Molybdenum	2.5	16.3	<	<
Nickel	7.5	48.9	117.6 ± 4.7	25.9 ± 23.1
Selenium	NA	7.1	0.31 ± 0.16	NA
Zinc	2.5	993.7	42.7 ± 3.0	51.5 ± 2.2

*USEPA (2009).
**indicates soil test below detection.

separated by ten meter buffer strips to prevent overlap. The application rate was determined as the N-based agronomic rate which met the crop N requirement. Perennial Utah rangeland grasses with good to excellent forage value include Wheatgrass, Bromegrass, Fescue, Ricegrass and Blue Gramma as well as several other species. The N requirement for rangeland grasses can vary from approximately 110 kg N/ha to over 450 kg N/ha depending on species and vegetative density (Johnson, 1989). The agronomic rate in Mg/ha was determined based on the assumption that healthy rangeland would exhibit an N demand of 170 kg N/ha (USDA, 2000), and that healthy rangeland would be dominated by perennial grass species (McFarland, 2001). It is important to note, that in estimating the agronomic rate, it is assumed only background nitrate and ammonia nitrogen are available for plant uptake (Equation 1).

$$\text{Agronomic Rate}\frac{\text{Mg}}{\text{ha}} = \frac{\text{adjusted nitrogen fertilizer requirement}\ \frac{\text{kg N}}{\text{ha}}}{\text{plant available nitrogen per tonne of biosolids}\frac{\text{kg N}}{\text{Mg}}}$$

$$\frac{\text{ANR}\ \frac{\text{kg N}}{\text{ha}}}{=\left(NO_3\right)+K_v\bullet\left(NH_4\right)+K_{min}\bullet\left(N_o\right)}$$

where:
ANR - Adjusted nitrogen fertilizer requirement (crop nitrogen requirement minus nitrate plus ammonia content found in soil) - (kg N/ha).
NO_3 - nitrate concentration in biosolids (kg N/mt).
NH_4 - ammonia concentration in biosolids (kg N/mt).
N_o - organic nitrogen concentration in biosolids (total nitrogen content found in biosolids minus nitrate plus ammonia content).
K_v - volatilization factor (0.5 since biosolids are not tilled into soil). K_{min}
- organic nitrogen mineralization rate (from McFarland, 2001).

A control plot, which served as a treatment performance baseline, was established and received no amendments. Details of biosolids application rates are displayed in Table 3.

Soil sampling

Eight of nine currently regulated heavy metals (As, Cd, Cu, Pb, Mo, Ni, Se and Zn) were recorded as a function of soil depth. Due to a limited analytical budget, As and Se concentrations were only recorded in Year 1, and mercury (Hg) was not recorded in either Year 1 or Year 2.

Concentrations of Cd, Cu, Pb, Mo, Ni and Zn were recorded after Year 1 and Year 2 following biosolids application. Soil sample volume was 0.5 liters. One borehole per test plot section was drilled using standard (8.26 cm. diameter) hand augers. Biosolids layers were removed before sampling.

To facilitate the selection of random samples, each of the 0.13 ha test plots was divided into 144 three by three meter sections (test plot sections). Six of the 144 test plot sections were selected using Microsoft Excel's random number generator. Samples were taken at 0.2, 0.6, 0.9, 1.2 and 1.5 m depths. Exact boundaries of each test plot section were established using a global positioning system (GPS).

Soil analysis

Soil samples were analyzed at Utah State University Analytical Laboratories using procedures described by Gavlak et al. (2003). Total metal contents (As, Cd, Cu, Pb, Mo, Ni, Se, and Zn) were measured using Open Vessel Digestion and Dissolution (for acid recoverable metals), which followed closely the EPA 3050A Method (Edgell, 1988 and Gavlak et al., 2003).

A nitric extraction/dissolution, along with heating on a hot plate was utilized. Digest analyte concentrations were determined using inductively coupled plasma atomic emission spectrometry (ICP-AES). Method detection limits (MDL) are 2.5 mg/kg for Cu, Mo, Pb, and Zn.

The MDL limits for Cd and Ni are 1.5 and 7.5 mg/kg, respectively. Values below MDL are represented by "<". The MDL was based on dry weight. (Table 2)

Statistical analysis

Statistical analyses were conducted using a "Fixed Effect Analysis of Variance with One Treatment Factor" in the Statistical Analysis System (SAS-Version 8). The null hypothesis (H_o) was that metal levels in biosolids amended rangeland soils were not statistically different from the control at the 95% confidence level (p-value is 5%).

The alternative hypothesis (H_a) assumed that metal levels were statistically different from the control at 95% confidence level. The

Table 3. Summary of biosolids land application rates.

Biosolids application rate (metric tonne/ha)		
Multiple of agronomic rate	**Lime stabilized biosolids**	**Aerobically digested biosolids**
1x	109.7	3.6
5x	548.5	18.1
10x	1097.0	36.3
20x	NA	72.5

Table 4. Arsenic level in soil (mg/kg) in the first year following application of biosolids applied at Specified multiplies of the agronomic rate.

Lime-stabilized Biosolids			**Aerobically-digested Biosolids**		
Depth (m)	**Mean**	**SE***	**Depth (m)**	**Mean**	**SE***
Control			**Control**		
0.2	4.80	0.50	0.2	4.80	0.50
0.6	6.40	0.70	0.6	6.40	0.70
0.9	8.90	1.40	0.9	8.90	1.40
1.2	7.60	0.90	1.2	7.60	0.90
1.5	14.10	0.70	1.5	14.10	0.70
1x Agronomic r Rate			1X Agronomic Rate		
0.2	4.62	0.24	0.2	10.78	6.68
0.6	5.71	0.41	0.6	5.33	0.37
0.9	8.10	0.90	0.9	7.71	0.71
1.2	7.74	0.55	1.2	7.15	0.46
1.5	10.29	0.40	1.5	10.64	0.49
5x Agronomic Rate			5x Agronomic Rate		
0.2	4.54	0.24	0.2	4.45	0.25
0.6	6.48	0.40	0.6	5.80	0.38
0.9	8.76	0.70	0.9	8.31	0.74
1.2	7.07	0.49	1.2	7.89	0.48
1.5	10.20	0.46	1.5	10.65	0.42
10x Agronomic Rate			10x Agronomic Rate		
0.2	4.68	0.25	0.2	4.37	0.30
0.6	6.20	0.49	0.6	5.80	0.38
0.9	9.24	0.72	0.9	7.60	0.71
1.2	7.85	0.57	1.2	8.10	0.53
1.5	11.16	0.58	1.5	10.2	0.37
			20x Agronomic Rate		
Not applied at higher rate			0.2	4.82	0.45
			0.6	5.81	0.37
			0.9	8.55	0.95
			1.2	7.85	0.61
			1.5	10.87	0.42

*Mean standard error of six replicates.

Table 5. Copper level in soil (mg/kg) one and two years following application of biosolids at specified multiples of the agronomic rate.

Lime-stabilized biosolids					Aerobically-digested biosolids				
	Year 1		Year 2			Year 1		Year 2	
Dept(m)	Mean	SE*	Mean	SE*	Dept(m)	Mean	SE*	Mean	SE*
	Control					Control			
0.20	<**	<	9.20	0.70	0.20	<	<	9.20	0.70
0.60	<	<	6.60	0.70	0.60	<	<	6.60	0.70
0.90	<	<	7.30	0.80	0.90	<	<	7.30	0.80
1.20	<	<	7.40	0.60	1.20	<	<	7.40	0.60
1.50	<	<	7.50	0.90	1.50	<	<	7.50	0.90
	1x Agronomic Rate					1x Agronomic Rate			
0.20	<	<	13.46	8.91	0.20	<	<	<	<
0.60	<	<	12.70	10.12	0.60	<	<	<	<
0.90	<	<	7.80	2.15	0.90	<	<	<	<
1.20	<	<	11.07	6.50	1.20	<	<	<	<
1.50	<	<	13.92	9.33	1.50	<	<	<	<
	5x Agronomic Rate					5x Agronomic Rate			
0.20	<	<	7.18	1.15	0.20	<	<	<	<
0.60	<	<	5.70	1.25	0.60	<	<	<	<
0.90	<	<	6.50	1.48	0.90	<	<	5.34	1.18
1.20	<	<	5.91	1.02	1.20	6.32	1.51	5.37	0.98
1.50	<	<	5.79	1.43	1.50	<	<	<	<
	10x Agronomic Rate					10x Agronomic Rate			
0.20	<	<	<	<	0.20	5.67	2.32	9.35	4.24
0.60	<	<	<	<	0.60	7.94	0.46	16.57	19.74
0.90	<	<	5.12	1.00	0.90	7.72	0.87	5.90	1.48
1.20	<	<	5.18	0.80	1.20	10.46	1.19	5.75	1.09
1.50	<	<	6.02	1.59	1.50	5.56	1.00	<	<
						20x Agronomic Rate			
					0.20	12.98	1.12	<	<
					0.60	8.34	1.24	<	<
Not applied at higher rate					0.90	6.09	1.44	<	<
					1.20	6.40	1.36	5.93	1.32
					1.50	4.90	2.25	5.81	1.43

*Mean stardard error of six replicate

**"<" indicates soil test below detected (5.0 mg/kg).

null hypothesis would be rejected if the p-value were less than 5%.

RESULTS

Arsenic

Arsenic levels (Table 4) increased along soil depths (that is 0.2 - 1.5 m) for all application rates; however, they were not statistically different from the control. Arsenic accumulation at the soil surface (that is 0.2 m) was not found.

Copper

Copper concentrations did not show a consistent trend as biosolids application rate increased with lime stabilized biosolids (Table 5). Increasing Cu concentrations were found along soil depths for the 1x treatment (one time agronomic rate) at the end of Year 2, but the standard errors indicate that these values are not significantly different from the controls. The significant increase in Cu content in the control soils in year 2 is likely due to the natural dynamics of Cu solubility and random sampling error. There were no additions of Cu to the control sites over the study period. Copper in soil amended with aerobically digested biosolids (Table 5) increased at test sites receiving higher loadings in Year 1 (at the 10x and 20x application levels).

This increase did not carry over into Year 2 where the soil Cu content returned to control soil levels, or within analytical error of the control soil levels.

The analysis of the Cu data is somewhat problematic given that soil test levels were so close to the detection limits for analysis; however, no consistent trends were noted for increases in Cu due to biosolids application. In those cases where numerical increases were observed (as noted above) the sampling and analytical error in this study did not result in any statistical differences. This is typical of the technologies used to spread biosolids in the field, and sample soils in large field-sized plot areas. The spatial variability in amendment distribution and the resulting cost-prohibitive sampling regime required to capture that variability, often make it difficult to track trends. It is important to note however that the small, non-statistical numerical increases noted for Cu were well below regulatory limits and, therefore, scientifically trivial.

Nickel

Nickel concentrations significantly decreased from Year 1 to Year 2 in the control and test sites that received lime stabilized and aerobically digested biosolids (Table 6). In such a case, one could cite as cause, random sampling error and spatial variability, but the result carries into all the treated plots as well. As yet there is no explanation for the reduction. Nickel is neither volatile nor mobile in soils to any great extent. That, coupled with the low natural precipitation in the area, would lead one to not expect any movement of Ni out of the soil profile. The fact that all samples in Year 2 exhibited this reduction at all biosolids application levels indicates this is a real reduction which warrants follow up sampling in the future. Further investigation should focus on metal translocation in treated soils, and plant uptake and removal of individual metals.

Selenium

No Se accumulation was found in most biosolids-amended soils one year following biosolids land application. Data did not show any consistent trend for Se concentrations along soil depths and at different application rates (Table 7).

Zinc

Most of the treatments in both Years 1 and 2 exhibited adecrease in Zn concentration along the soil depth profile, but Zn levels appeared to increase for lime stabilized treated soils. Test sites receiving aerobically digested biosolids seemed to have decreasing Zn concentrations from Year 1 to Year 2 following biosolids application (Table 8). In addition, Zn tended to accumulate at the soil surface (e.g. 0.2 m) in both years.

Cadmiun, lead and molybdenum

Cadmium, Lead and Molybdenum concentrations were all below MDL (1.5, 2.5 and 2.5 mg/kg, respectively) and thus not reported in the tables.

Discussion and Conclusion

There was no consistent trend for accumulation of any metal (As, Cd, Cu, Pb, Mo, Ni, Se and Zn) in either Year 1 or Year 2. This was not surprising when considering the impact of localized environmental conditions on metal mobility and leaching. In general, most metal concentrations did not exhibit significant discrepancies compared to the control. The concentrations of metals in this work were below the cumulative loading rate limits established by the 40 CFR Part 503 rule for biosolids-amended soils (Table 9). This may be explained by noting that metals in all biosolids are strictly regulated at wastewater treatment plants before they are applied forany beneficial use. In other words, biosolids must meet strict metal criteria (McFarland, 2001) before being marketed or land applied.

Arsenic did not accumulate at soil surfaces relative to the control, but did tend to increase with soil depth. This As behavior can be understood in light of the impact of P on As mobility. It should be noted that As exists as As(III) or As(V) in the soil environment with As(III) predominating as soil pH increases. Soil pH is a key factor in the adsorption of As(III) as a previous study (Pierce and Moore, 1980) showed maximum adsorption of As(III) by iron oxide at pH 7. However, with high concentrations of phosphorus in biosolids, As tends to become more mobile since phosphorus can displace As on adsorption sites. This could lead to As leachability or plant uptake of As and may partially explain the lack of As accumulation within the upper reaches of the soil column. As(III) is more highly leachable than As(V) due to its high solubility. However, As(III) could be oxidized to As(V) in the presence of manganese oxide which serves as a primary electron acceptor. Compared to the control, As concentrations were not significantly different at various soil depths. Arsenic concentrations were below the cumulative loading rate limit.

Copper was well below cumulative loading rate limits from the 40 CFR Part 503 rule. However, copper did not exhibit any consistent trend among soils amended with two different types of biosolids. Increasing copper concentrations from Year 1 to Year 2 were found in soils that had received lime stabilized biosolids; meanwhile the

Table 6. Nickel level in soil (mg/kg) one and two years following application of biosolids at specified multiples of the agronomic rate.

Lime stabilized Biosolids					**Aerobically-digested Biosolids**				
	Year 1		**Year 2**			**Year 1**		**Year 2**	
Dept (m)	**Mean**	**SE***	**Mean**	**SE***	**Dept (m)**	**Mean**	**SE***	**Mean**	**SE***
	Control					**Control**			
0.20	117.60	4.70	25.90	23.10	0.20	117.60	4.70	25.90	23.10
0.60	127.90	9.00	23.10	2.10	0.60	127.90	9.00	23.10	2.10
0.90	118.10	5.80	25.70	1.90	0.90	118.10	5.80	25.70	1.90
1.20	132.20	2.30	25.30	1.60	1.20	132.20	2.30	25.30	1.60
1.50	111.10	7.80	27.00	1.70	1.50	111.10	7.80	27.00	1.70
	1x Agronomic Rate					1x Agronomic Rate			
0.20	116.46	3.29	33.78	18.11	0.20	93.76	2.73	26.58	8.14
0.60	124.67	8.50	23.73	6.02	0.60	97.93	5.23	22.21	6.55
0.90	116.55	4.19	21.97	2.83	0.90	113.53	12.42	21.02	3.73
1.20	118.7	4.73	28.81	13.53	1.20	121.03	12.79	20.48	4.34
1.50	111.24	5.55	31.63	15.40	1.50	88.52	4.73	25.56	6.17
	5x Agronomic Rate					5x Agronomic Rate			
0.20	98.5	0.29	21.01	6.26	0.20	114.7	3.15	22.62	6.59
0.60	111.95	0.47	18.96	5.94	0.60	112.95	6.30	19.48	6.11
0.90	115.63	0.69	17.46	2.30	0.90	116.8	3.24	18.69	3.46
1.20	112.52	1.17	17.37	1.99	1.20	126.27	3.82	17.94	2.53
1.50	104.98	0..93	18.82	2.40	1.50	89.35	4.95	<**	<
	10x Agronomic Rate					10x Agronomic Rate			
0.20	100.68	5.06	24.26	7.36	0.20	97.21	6.96	24.61	6.94
0.60	111.32	7.72	20.62	6.87	0.60	100.84	4.87	25.64	8.07
0.90	105.17	5.59	20.01	5.35	0.90	96.85	3.29	21.69	4.32
1.20	105.83	5.96	19.3	4.43	1.20	122.14	15.81	31.61	10.55
1.50	96.08	7.30	24.18	5.44	1.50	84.09	3.97	20.83	3.51
						10x Agronomic Rate			
					0.20	97.14	6.27	25.42	8.32
					0.60	108.22	7.93	23.25	6.90
	Not applied at higher rate				0.90	118.22	14.21	20.66	4.41
					1.20	113.8	8.64	18.23	2.89
					1.50	104.05	9.40	<	<

* Mean standard error of six replicates.
**"<" indicates soil test below detection (15.0 mg/kg).

the opposite trend existed in soils that had received aerobically digested biosolids. In many cases, copper accumulation was found at 0.2 - 1.2 m depths as copper concentrations in biosolids-amended soils were statistically different from the control plot. Ippolito et al. (2009) found that surface applied biosolids enhanced the downward movement of organically complexed Cu in a similar environment and that Cu bioavailability is dependent on the level of dissolved specie which decreases with depth.

Nickel concentrations decreased from Year 1 to Year 2 in both biosolids -amended soils, possibly from plant uptake (Vasquez, 2008). Vasquez (2008) suggests that plant uptake of Ni occurs, but that levels in plants are below tolerable limits. Additionally, Ni is retained in soil through adsorption to iron and manganese oxides as well as organic matter (McLean and Bledsoe, 1992). Most Ni concentrations were below the cumulative loading rate limit. Under prevalent oxidizing conditions, accumulation of Cu, Zn, and Ni was present within the soil surface, which is indicative of the immobility of these metals. High soil pH in biosolids-amended rangelands is favorable for

Table 7. Selenium level in soil (mg/kg) in the first year following appli-cation of Bio-solids applied at specified.

Lime-stabilized Biosolids			**Aerobically-digested Biosolids**		
Dept (m)	**Mean**	**SE***	**Dept (m)**	**Mean**	**SE***
Control			**Control**		
0.2	0.31	0.16	0.2	0.31	0.16
0.6	0.59	0.06	0.6	0.59	0.06
0.9	0.40	0.21	0.9	0.40	0.21
1.2	0.25	0.13	1.2	0.25	0.13
1.5	0.54	0.19	1.5	0.54	0.19
1x Agronomic Rate			1x Agronomic Rate		
0.2	NA**	NA	0.2	0.22	0.10
0.6	NA	NA	0.6	5.25	5.03
0.9	0.22	0.10	0.9	0.28	0.13
1.2	0.13	0.06	1.2	0.25	0.13
1.5	0.27	0.09	1.5	0.33	0.11
5x Agronomic Rate			5x Agronomic Rate		
0.2	0.24	0.11	0.2	0.43	0.09
0.6	5.25	5.02	0.6	5.42	5.03
0.9	0.32	0.15	0.9	0.54	0.11
1.2	0.19	0.09	1.2	0.38	0.07
1.5	0.36	0.13	1.5	0.55	0.10
10x Agronomic Rate			10x Agronomic Rate		
0.2	0.51	0.12	0.2	0.44	0.08
0.6	5.50	5.03	0.6	5.51	5.03
0.9	0.46	0.12	0.9	0.5	0.11
1.2	0.34	0.06	1.2	0.44	0.06
1.5	0.62	0.13	1.5	0.55	0.10
			20x Agronomic Rate		
Not applied at higher rate			0.2	0.34	0.13
			0.6	5.49	5.02
			0.9	0.42	0.15
			1.2	0.29	0.11
			1.5	0.46	0.14

* Mean standard error replicates.

** NA indicates soil test below detection.

Zn adsorption. Additionally, hydrolyzed species of Zn, which occurs at pH > 7.7, are strongly adsorbed to the soil surface (McLean and Bledsoe, 1992). Soil retention of Cu and especially Ni is strong through adsorption mechanisms. Soil amended with lime stabilized biosolids had lower Se levels than soil amended with aerobically digested biosolids applied at rates equivalent to 1 and 5x the estimated agronomic rate in Year 1. However, due to high soil pH, Se in the test treatments with lime stabilized biosolids can be more mobile than Se in the test treatments with aerobically digested biosolids. Within the soil surface (0.2 m), statistical analyses suggested that Se accumulation in the biosolids-amended test sites did not exist. This suggests significant Se mobility associated with high soil pH and oxidizing conditions. In addition, the elevated concentrations of P in biosolids could enhance Se mobility since P, especially as phosphate, strongly adsorbs to soils and can displace Se. In general, Se in biosolids-amended soils was well below the concentration limit required by the 40 CFR Part 503 rule.

Zinc exhibited a similar tendency to Cu in both biosolids-amended soils, and was found to accumulate at

Table 8. Zinc level in soil (mg/kg) one and two years following application of biosolids at specified multiples of the agronomic rate.

Lime-stabilized Biosolids					Aerobically-digested Biosolids				
	Year 1		Year 2			Year 1		Year 2	
Dept(m)	Mean	SE*	Mean	SE*	Dept(m)	Mean	SE*	Mean	SE*
	Control					Control			
0.20	42.70	3.00	51.50	2.20	0.20	42.70	3.00	51.50	2.20
0.60	37.40	0.70	43.00	2.40	0.60	37.40	0.70	43.00	2.40
0.90	37.90	3.50	45.30	1.80	0.90	37.90	3.50	45.30	1.80
1.20	31.70	2.10	41.30	1.70	1.20	31.70	2.10	41.30	1.70
1.50	35.90	2.30	46.60	1.10	1.50	35.90	2.30	46.60	1.10
	1x Agronomic Rate					1x Agronomic Rate			
0.20	40.04	1.58	83.56	39.08	0.20	44.53	1.74	46.48	2.61
0.60	115.12	83.46	52.8	1.55	0.60	34.70	0.40	37.03	3.14
0.90	34.00	2.05	54.5	3.00	0.90	38.55	2.05	40.88	2.79
1.20	32.09	1.73	50.49	1.87	1.20	35.30	1.29	40.68	2.59
1.50	36.76	1.17	76.18	91.86	1.50	39.38	1.19	44.09	1.90
	5x Agronomic Rate					5x Agronomic Rate			
0.20	40.4	2.13	53.07	4.09	0.20	48.09	3.01	51.81	3.19
0.60	36.93	2.92	45.11	4.73	0.60	39.8	1.03	43.21	3.65
0.90	39.44	1.99	48.38	3.99	0.90	41.07	2.02	45.76	2.70
1.20	37.37	1.36	44.62	3.26	1.20	40.68	2.35	44.68	2.40
1.50	34.81	4.40	45.68	4.36	1.50	36.76	2.15	42.79	3.53
	10x Agronomic Rate					10x Agronomic Rate			
0.20	50.13	2.06	49.11	2.78	0.20	44.73	3.96	50.37	3.00
0.60	37.8	1.07	42.13	3.05	0.60	37.29	0.44	42.34	2.80
0.90	40.63	2.60	45.88	2.58	0.90	38.15	1.96	44.47	2.53
1.20	30.49	1.19	38.58	2.44	1.20	39.4	1.09	42.00	2.46
1.50	34.72	1.81	52.78	4.28	1.50	34.77	1.47	42.38	2.05
						20x Agronomic Rate			
					0.20	54.42	5.30	50.25	2.62
					0.60	40.52	2.57	41.45	3.05
	Not applied at higher rate				0.90	40.09	2.88	46.21	2.51
					1.20	39.26	5.71	44.27	4.04
					1.50	40.43	4.84	42.25	1.95

* Mean standard error of six replicates.

Table 9. Metal loading rate limits for land-applied biosolids.

	Cumulative loading rate limits	
Metal	Kg/ha	Mg/kg*
As	41	10
Cd	39	9
Cu	1500	362
Pb	300	72
Hg	17	4
Ni	420	101
Se	100	24
Zn	2800	675

*Converted to soil concentration assuming 30.5-cm depth and a bulk density of 1.36 g/cm^3.

soil surfaces in both years. Additionally, Zn was found to accumulate at depths of 0.6 - 1.2 m in both years based on statistical analyses. All Zn concentrations were well below the cumulative loading rate limit.

Overall, the cumulative loading rates of eight regulated metals (As, Cd, Cu, Pb, Mo, Ni, Se, and Zn) in this study were below the standard limits from the 40 CFR Part 503 Rule for biosolids-amended soils. Thus, our biosolids application posed no risk to human health, animals, or the environment with respect to potential metal accumulation.

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