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PREDICTING SOIL-EXTRACTABLE ZN, P, FE, AND CU IN A BIOSOLIDS-AMENDED DRYLAND WHEAT AGROECOSYSTEM

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Biosolids Beneficial Use Programs frequently involve multiple applications at agronomic rates, with plant-nutrient availability changing as elements react with soil constituents over time. Consequently, can regression equations reasonably estimate plant availability of Zn, P, Fe, and Cu, where multiple applications of Littleton and Englewood, Colorado Wastewater Treatment Plant biosolids are applied to a dryland wheat (*Triticum aestivum* L.)-fallow agroecosystem? Before each growing season, we added Littleton and Englewood biosolids at rates of 0 to 11.2 dry Mg ha^{-1} to plots arranged in randomized complete blocks with four replications per treatment. Soil samples collected after each wheat harvest were analyzed using an NH_4HCO_3-diethylenetriaminepentaacetic acid extraction. We completed planar (included the number of applications and elemental additions), linear, quadratic, and exponential-rise-to-a-maximum (as a function of elemental additions only) regression analyses for six applications at two sites. We found that the planar regression models provided superior R^2 values and SE of the estimate in almost all cases. These results suggest that lability changes as biosolids-borne Zn, P, Fe, and Cu react with the soil over time. Consequently, predictions of nutrient availability involving multiple biosolids applications to dryland wheat-fallow agroecosystems should account for the number of biosolids additions. (Soil Science 2008;173:175–185)

Key words: Planar regression, regression equations, diethylenetriaminepentaacetic acid, lability.

THE USEPA (1993) promotes biosolids recycling on cropland because this material can supply plant nutrients such as Zn, P, Fe, and Cu. Applications are typically based on agronomic N rates, and multiple additions over time are common. Two questions concerning this multiple-application practice are: (i) How do various regression models compare in predicting nutrient lability? and (ii) How does the prediction for six continuous applications after six croppings compare, in terms of plant-nutrient availability, to the prediction for a single application after one cropping?

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Apparently, biosolids-borne nutrients decline in availability over time when application ceases or after a single addition. Bidwell and Dowdy (1987) showed that corn stover and grain Zn concentrations decreased 6 years after biosolids termination, suggesting that biosolids-applied Zn was converted to more stable forms over time. Barbarick and Ippolito (2003) found that only three dryland wheat croppings after biosolids application termination were needed before NH_4HCO_3-diethylenetriaminepentaacetic acid (AB-DTPA) Zn and P levels approached those of untreated controls. They suggested the biosolids-borne Zn and P were transformed to less soluble mineral phases or were adsorbed onto mineral surfaces. Sukkariyah et al. (2005) reported DTPA-extractable Cu and Zn decreased by 58% and 42%, respectively, 17 years after a single biosolids application added 760 kg Cu ha^{-1} and 620 kg Zn ha^{-1}. Hseu (2006) observed a decrease in DTPA-extractable Zn over time in soils treated with 20.3, 102, and 203 kg

TABLE 1

Concentrations of selected elements in biosolids from the Metropolitan Sanitary District of Greater Chicago used in a national research study

Element	Concentration ± S.D.	Elemental additions with 100 Mg biosolids ha^{-1} kg ha^{-1}
P, g kg^{-1}	20.0 ± na[†]	2000
Cu, mg kg^{-1}	1330 ± 92	130
Fe, g kg^{-1}	30.4 ± 1.5	3040
Ni, mg kg^{-1}	721 ± 31	72
Zn, mg kg^{-1}	4800 ± 274	480

[†]na: data not available.
(adapted from Sommers et al., 1991)

Zn ha^{-1} (10, 50, and 100 Mg biosolids ha^{-1} containing 2030 mg Zn kg^{-1}).

Multiple biosolids applications create dynamic changes in nutrient availability. Berti and Jacobs (1996) found that water-soluble and exchangeable (both are considered to be plant-available) Zn and Cu significantly increased with biosolids additions. Sloan et al. (1997) showed that exchangeable and specifically adsorbed Zn increased after a 20-year biosolids watershed application study. Conversely, Gaskin et al. (2003) indicated that several biosolids applications to bermudagrass (*Cynodon dactylon* [L.] Pers.) pastures produced forage that was the same quality as that found where commercial fertilizers were used.

A regional research project that involved 16 sites in 15 states was initiated in 1978 to study the trace element uptake by barley (*Hordeum vulgare*) in soils amended with Chicago biosolids (Table 1) with either five applications of 20 Mg ha^{-1} or a single addition of 100 Mg ha^{-1} (Sommers et al., 1991). Changes in crop uptake, $NaHCO_3$-extractable P, and DTPA-extractable trace elements were determined each year during a 5-year period. Sommers et al. (1991) concluded that at the end of the fifth year, the multiple or single biosolids application produced similar extractable P and trace element concentrations in surface soils (top 15 cm) over all sites. At individual sites with more complete data sets (Table 2), treatment timing significantly affected DTPA Cu and Zn. The DTPA-extractable Cu or Zn concentrations for the fifth year were smaller at the Arizona, Colorado, Florida, and Nebraska sites for the five applications of 20 Mg Chicago biosolids ha^{-1} compared with a single application of 100 Mg ha^{-1}.

To further enhance the understanding of multiple biosolids land applications, we tested two hypotheses:

Planar regression models that predict AB-DTPA–extractable Zn, P, Cu, and Fe as a function

TABLE 2

Summary of selected data after year 5 for soils with surface pH greater than or equal to 6 from the national research study where Chicago biosolids were applied to barley at several locations, with five annual applications of 20 Mg ha^{-1} or a single application of 100 Mg ha^{-1}

	pH	$NaHCO_3$ P	DTPA Cu	DTPA Zn
		------ mg kg^{-1} ------		
Arizona: Pima clay loam, Typic Torrifluvent				
5 App[†] of 20 Mg ha^{-1}	7.8	116	15	47
1 App of 100 Mg ha^{-1}	7.7	60	16	55
California: Domino loam, Xerollic Calciorthid				
5 App of 20 Mg ha^{-1}	7.2	39	9	31
1 App of 100 Mg ha^{-1}	7.3	37	6	19
California: Greenfield sandy loam, Typic Haploxeralf				
5 App of 20 Mg ha^{-1}	7.0	36	10	37
1 App of 100 Mg ha^{-1}	7.1	22	4	17
Colorado: Nocono clay loam, Aridic Argiustoll				
5 App of 20 Mg ha^{-1}	na[‡]	na	6	19
1 App of 100 Mg ha^{-1}	na	na	19	40
Florida: Lake fine sand, Typic Quartzipsamment				
5 App of 20 Mg ha^{-1}	6.2	41	16	41
1 App of 100 Mg ha^{-1}	6.3	40	23	62
Nebraska: Sharpsburg silty clay loam, Typic Argiudoll				
5 App of 20 Mg ha^{-1}	6.8	44	14	55
1 App of 100 Mg ha^{-1}	6.8	41	16	53
Ohio: Celina silt loam, Aquic Hapludalf				
5 App of 20 Mg ha^{-1}	6.2	90	15	44
1 App of 100 Mg ha^{-1}	6.2	81	8	22

Summary of selected data after year 5 for soils with surface (0 to 15 cm) pH greater than or equal to 6 from the national research study where Chicago biosolids were applied to barley (*Hordeum vulgare*) at several locations (Sommers et al. 1991), with five annual applications of 20 Mg ha^{-1} or a single application of 100 Mg ha^{-1}.
[†]App: application(s); [‡]na: data not available.

TABLE 3

The Zn, P, and Cu content of the L/E, Colorado biosolids applied to dryland winter wheat at two sites near Bennett, Colorado, from 1993 to 2005

Site A					Site B				
Yr applied	Zn, mg kg^{-1}	P, g kg^{-1}	Cu, mg kg^{-1}	Fe, g kg^{-1}	Yr applied	Zn, mg kg^{-1}	P, g kg^{-1}	Cu, mg kg^{-1}	Fe, g kg^{-1}
1993	942	27.1	558	15.2	1994	816	16.6	493	11.1
1995	816	17.4	458	12.0	1996	652	23.0	657	17.0
1997	422	35.9	459	15.1	1998	301	11.8	236	13.7
1999	198	10.2	256	19.2	2000	370	36.0	352	18.0
2001	428	19.9	398	26.3	2002	351	19.3	326	19.7
2003	418	24.2	594	21.0	2004	767	29.8	652	36.7
Total element added with 11.2 Mg biosolids ha^{-1} rate kg ha^{-1}	36	1510	30	1220	Total element added with 11.2 Mg biosolids ha^{-1} rate kg ha^{-1}	36	1530	30	1300

of the number of applications plus the quantity of each element applied will provide superior predictability based on R^2 values and SE compared with linear, quadratic, and exponential-rise-to-a-maximum models.

Planar regression models will predict that six continuous biosolids applications will require larger amounts of applied Zn, P, and Fe after six croppings than a comparable single biosolids application after one cropping to reach 1.5 mg AB-DTPA Zn kg^{-1}, 20 mg AB-DTPA P kg^{-1}, and 10 mg AB-DTPA Fe kg^{-1}. The 1.5-mg AB-DTPA Zn kg^{-1} and 10-mg AB-DTPA Fe kg^{-1} levels represent an adequate amount for plant growth (Mortvedt and Westfall, 2004), whereas the 20-mg AB-DTPA P kg^{-1} is considered high for the Colorado P Risk Index (Sharkoff et al., 2006).

MATERIALS AND METHODS

We began our biosolids study in the summer of 1993 near Bennett, Colorado. Mean annual precipitation for this area is about 350 mm, mean maximum and minimum temperatures are 19 °C and 2 °C, respectively, and the annual growing season is about 150 days (NRCS, 1974). Because the crop rotation was

TABLE 4

Regression model R^2 values and SE for AB-DTPA–extractable Zn, P, Cu, and Fe after six applications of L/E biosolids

Nutrient	Regression model	Site A R^2	Site A SE	Site B R^2	Site B SE
Zn	Planar[†]	0.747	0.39	0.671	0.32
	Linear	0.733	0.39	0.554	0.37
	Quadratic	0.742	0.39	0.558	0.37
	Exp. rise to max.	0.744	0.39	Model did not fit	
P	Planar	Significant interaction of P added by number of applications		0.622	2.8
	Linear			0.511	3.2
	Quadratic			0.412	3.2
	Exp. rise to max.			0.511	3.2
Cu	Planar	0.859	0.36	0.906	0.27
	Linear	0.613	0.58	0.874	0.30
	Quadratic	0.616	0.59	0.877	0.31
	Exp. rise to max.	Model did not fit		0.859	0.31
Fe	Planar	0.924	0.75	0.816	0.68
	Linear	0.436	1.3	0.522	1.1
	Quadratic	0.480	1.3	0.523	1.1
	Exp. rise to max.	Model did not fit		Model did not fit	

[†]Probability levels for all regression analyses were less than 0.001.

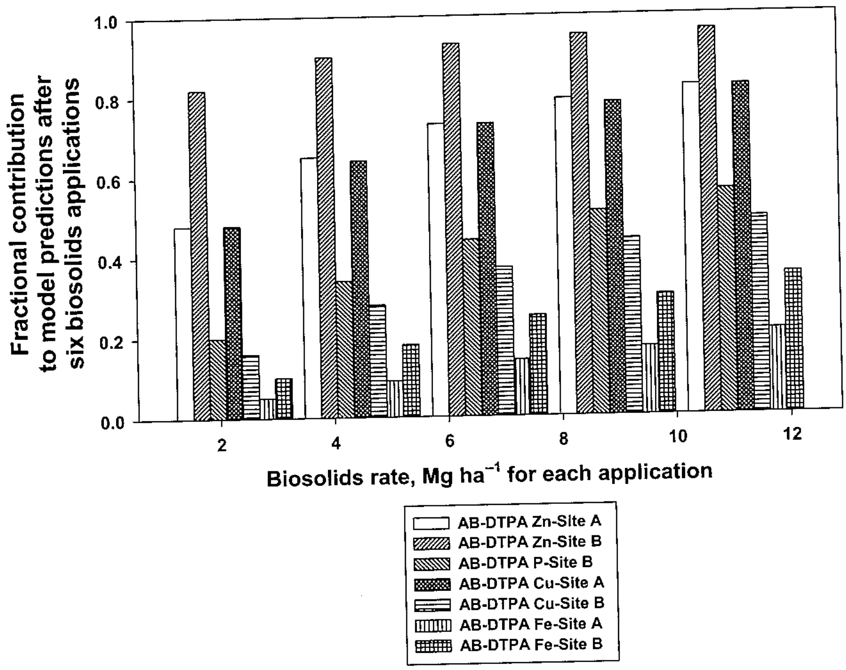


Fig. 1. Fractional contribution to AB-DTPA model predictions after six biosolids applications for all biosolids application rates.

hard red winter wheat-summer fallow, two sets of plots were used (designated A for those established in 1993; B for those established in 1994).

The soils at both sites were classified as Weld loam (fine, smectitic, mesic Aridic Argiustoll; NRCS, 2007a). The NRCS (2007b) estimates that the Weld soil series occupies 3.24×10^5 ha in eastern Colorado. Before biosolids application, organic matter content was less than or equal to 1% to a depth of 200 cm, surface (0−20 cm) soil pH was 6.9, and subsoil pH ranged from 7.2 to 8.3 from 20 to 200 cm in depth for the two sites. The electrical conductivity of saturated soil extracts were less than 1 dS m^{-1} at all depths, except the 150- to 200-cm depth at Site B (2.8 dS m^{-1}), and NO_3^-–N plus NH_4^+–N was less than 9 mg kg^{-1} for all depths at both sites.

The Littleton and Englewood (L/E) biosolids were anaerobically digested and supplied by L/E after approximately 60 days of sand-bed drying. Biosolids samples were collected before application and kept refrigerated at approximately 3 °C until analyses were completed. Table 3 shows the application sequence, with biosolids applied at rates of 0, 2.24, 4.48, 6.72, 8.96, and 11.2 dry Mg biosolids ha^{-1} to 1.8 by 17.1-m plots in 1993, 1995, 1997, 1999, 2001, and 2003 at Site A and in 1994, 1996, 1998, 2000, 2002, and 2004 at Site B. Table 3 also gives the biosolids characteristics and the elemental application amounts for each site for the highest biosolids rate (11.2 dry Mg biosolids ha^{-1}); Barbarick and Ippolito (2007) provide further details on plots set up. Biosolids rates bracket those commonly used on dryland wheat in Colorado (Barbarick and Ippolito, 2007). Four replications of all treatments were used in a randomized complete block design. In late July or early August (about 50 days before planting), the dried biosolids were weighed (solids content of 530–930 g kg^{-1}), evenly spread over the plots using a front-end loader, hand raked to improve the uniformity of distribution, and immediately incorporated to a depth of 10 to 15 cm with a rototiller.

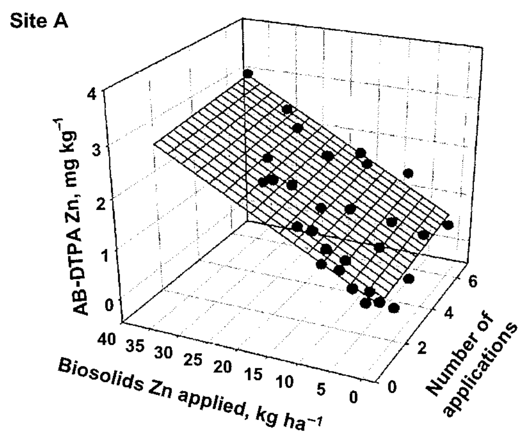
Immediately after each wheat harvest, composite soil samples were collected (two to three cores per plot) from the 0- to 20-cm (tillage layer) depth near the center of each plot. Samples were taken near the center of each plot to avoid biosolids redistribution problems that can occur after many tillage operations during several cropping years (Yingming and Corey, 1993). The soil samples were immediately air-dried and crushed to pass a 2-mm sieve. Soil concentrations of plant-available Zn, P, Fe, and Cu were determined in AB-DTPA extracts (Barbarick et al., 1997) using inductively coupled plasma-atomic emission spectrophotometer (Soltanpour et al., 1996).

We first analyzed the AB-DTPA data for each site using a split-plot analysis (Steel and Torrie, 1980), where biosolids rates were main plots and biosolids application frequency were the subplots. We separated the sites because plant growth and sampling took place during different growing seasons. We used a probability level (P) of 0.05 to determine significance. We determined if significant biosolids rate by application frequency interaction existed. If the interaction was not significant, we developed regression models using the biosolids rate and/or application frequency in calculating regression equations.

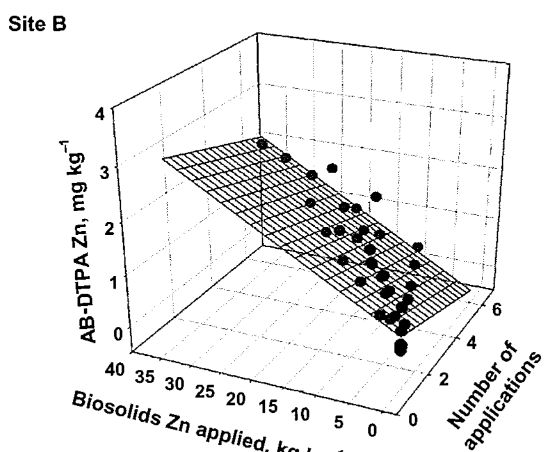
We completed regression analyses using the following models:

Planar:

$$\text{AB}-\text{DTPA} = a + b\,(\text{ amount of element added}) + c\,(\#\text{ applications}) \quad (1)$$



AB-DTPA Zn = 0.55 + 0.047(Biosolids applied Zn) + 0.062(Number of applications)
R^2 = 0.743; P < 0.001



AB-DTPA Zn = 0.096 + 0.33(Biosolids applied Zn) + 0.12(Number of applications)
R^2 = 0.671; P < 0.001

Fig. 2. Planar regression for AB-DTPA Zn versus amount of biosolids-borne Zn applied and number of biosolids applications at two dryland agroecosystem sites that received L/E biosolids.

Linear:

$$AB - DTPA = a + b(\text{amount of element added}) \quad (2)$$

Quadratic:

$$AB - DTPA = a + b(\text{amount of element added}) + c(\text{amount of element added})^2 \quad (3)$$

Exponential rise to a maximum:

$$AB - DTPA = a + b(1 - e^{-(\text{amount of element added})}) \quad (4)$$

where AB-DTPA = AB-DTPA–extractable concentration in mg kg^{-1} and a, b, c = empirical constants.

We used $P = 0.05$ to determine significance. Model equations, R^2 values, and SE were determined using SigmaPlot® (2006) version 10.

RESULTS AND DISCUSSION

The split-plot analyses showed that only Site A AB-DTPA P had a significant biosolids rate × application frequency interaction (statistical data not provided), although all analyses found significant main plot (biosolids application rate) and subplot (biosolids application frequency) effects. Consequently, we calculated regression models for AB-DTPA Zn, P (Site B only), Fe, and Cu using Eq.(1−4).

One of our goals was to compare various regression models for their suitability in predicting plant-available Zn, P, Fe, and Cu after six biosolids applications at two sites. Table 4 shows that for all but AB-DTPA P at Site A, the planar regression model Eq.(1) provided larger R^2 values and smaller SE than the other three models. We therefore accepted the first hypothesis that the planar regression model would provide better predictability compared with linear, quadratic, and exponential-rise-to-a-maximum models (Eq. 2−4).

Extrapolation with the planar regression may allow soil scientists and biosolids managers to predict, knowing application rates and number of applications, when they would reach a desired AB-DTPA–extractable Zn, P, Fe, or Cu concentration.

As shown in Fig. 1 for each element, the fractional contributions of the *amount of element applied* parameter to the change in model predictions above the control for all biosolids rates after six applications increased with increasing biosolids rate. Concomitantly, the contribution due to the *number of applications* parameter decreased as biosolids rate increased (data not shown). The amount of element applied produced greater than 50% of the change in predicted concentrations for Zn at both sites. In contrast, the amount of element applied produced less than 40% of the change in predicted Fe at both sites. Two factors probably contributed to these differences. First, an average of 35 times more Fe than Zn was added to both sites (Table 3). Second, the L/E treatment plant adds $Fe_2(SO_4)_3$ to reduce H_2S in the anaerobic-digester gas. These Fe materials may have a lower lability than the biosolids Zn.

Because the AB-DTPA Zn, P, Fe, and Cu concentrations were found to be a function of the number of applications and the amount of element supplied by the biosolids, the regression equations predict a three-dimensional planar relationship. Figures 2 through 5 provide the planar regression plots and predictive equations.

TABLE 5

Predicted biosolids Zn additions to reach adequate levels, biosolids P additions to reach high levels, and biosolids Fe additions to reach adequate levels using the planar regression models

	Site	6 Continuous applications	Single application
Biosolids Zn for 1.5 mg AB-DTPA Zn kg^{-1}, total kg Zn ha^{-1}	A	10.7	14.5
	B	20.7	39.2
Biosolids P for 20 mg AB-DTPA P kg^{-1}, total Mg P ha^{-1}	A	—	—
	B	1.8	2.8
Biosolids Fe for 10 mg AB-DTPA Fe kg^{-1}, total Mg Fe ha^{-1}	A	5.0	8.9
	B	3.5	5.5

Predicted biosolids Zn additions to reach adequate levels (1.5 mg AB-DTPA Zn kg^{-1}; Mortvedt and Westfall, 2004), biosolids P additions to reach high levels (20 mg AB-DTPA P kg^{-1}; Sharkoff et al., 2006), and biosolids Fe additions to reach adequate levels (10 mg AB-DTPA Fe kg^{-1}; Mortvedt and Westfall, 2004) using the planar regression models.

TABLE 6

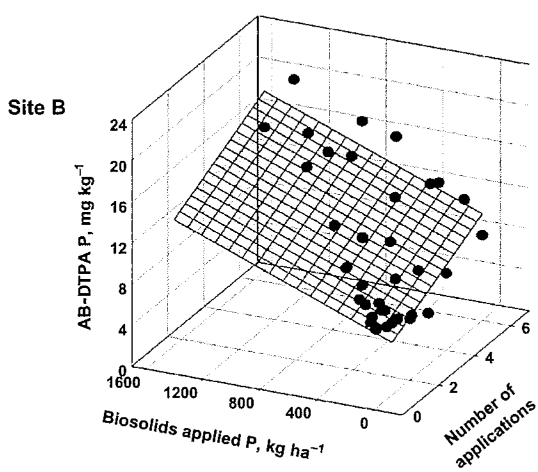
Number of hectares of Weld loam and associated soils classified as fine, smectitic, mesic Aridic Argiustolls

Soil series	State(s)	Total ha	Soil series	State(s)	Total ha
Weld	CO	3.4×10^5			
Bethune	CO	2.2×10^2	Nunn	CO, MT, SD, WY	3.5×10^5
Blackpipe	SD	2.6×10^4	Querc	WY	4.8×10^3
Boneek	SD, WY	2.4×10^4	Rednun	CO	1.6×10^3
Boquillas	AZ	3.1×10^3	Richfield	CO, KS, MT, NE, TX	1.0×10^6
Collbran	UT	3.2×10^3	Ryus	KS	2.8×10^3
Collide	CO	1.1×10^3	Savo	NE, SD	5.4×10^4
Emigrant	SD, WY	1.8×10^4	Showlow	AZ	8.5×10^4
Huggins	SD	2.1×10^4	Standely	CO	1.8×10^3
Kube	SD	2.2×10^3	Thunderbird	AZ, NM, NV	3.0×10^5
Leyden	CO	1.8×10^3	Wormser	CO, MT, WY	1.0×10^4
Nuncho	WY	1.3×10^4	Total		2.3×10^6

Number of hectares of Weld loam and associated soils classified as fine, smectitic, mesic Aridic Argiustolls (NRCS, 2007b). AZ: Arizona; CO: Colorado; KS: Kansas; MT: Montana; NE: Nebraska; NM: New Mexico; NV: Nevada; SD: South Dakota; TX: Texas; UT: Utah; WY: Wyoming.

We also hypothesized that planar-regression models will predict that six continuous biosolids applications will require larger amounts of applied Zn, P, and Fe after six croppings than a comparable single biosolids application after one cropping to reach adequate levels of Zn and Fe or high levels of P. We believe that this would result from the transformation of six smaller applications of the elements to less soluble mineral or adsorbed phases over six croppings as opposed to a single larger application after one cropping. Barbarick and Ippolito (2003) showed that once biosolids application ceases, only three croppings were required for AB-DTPA–extractable Zn and P to return to the same concentrations as the untreated control. They also suggested that

Site A: Because a significant biosolids applied P by number of applications interaction was found, planar regression analyses could not be completed.



AB-DTPA P = 4.0 + 0.0053(Biosolids applied P) + 1.05(Number of applications)

R^2 = 0.622; P < 0.001

Fig. 3. Planar regression for AB-DTPA P versus amount of biosolids-borne P applied and number of biosolids applications at two dryland agroecosystem sites that received L/E biosolids.

less soluble element forms developed after biosolids input was terminated. Bidwell and Dowdy (1987) showed that corn stover and grain Zn concentrations decreased six years after biosolids termination, suggesting that biosolids-applied Zn was converted to more stable chemical forms in the soil.

As shown in Table 2, Sommers et al. (1991) did not find consistent trends in $NaHCO_3$-extactable P or DTPA-extractable Cu and Zn after the fifth year for the comparison between five applications of Chicago biosolids at 20 Mg ha^{-1} for 5 years or a single application of 100 Mg ha^{-1}. They indicated that the total cumulative trace metal addition for several years is more critical than annual applications in terms of trace metal extractability by DTPA. What they did not discuss was if the application treatment produced trends at individual sites. Sommers et al. (1991) also concluded that after biosolids application, trace metal availability to plants will decrease over time.

We used the planar regression models shown in Fig. 2 to calculate how much biosolids-borne Zn would be needed to raise the AB-DTPA Zn concentration to 1.5 mg kg^{-1}. This Zn concentration is considered adequate for Colorado soils

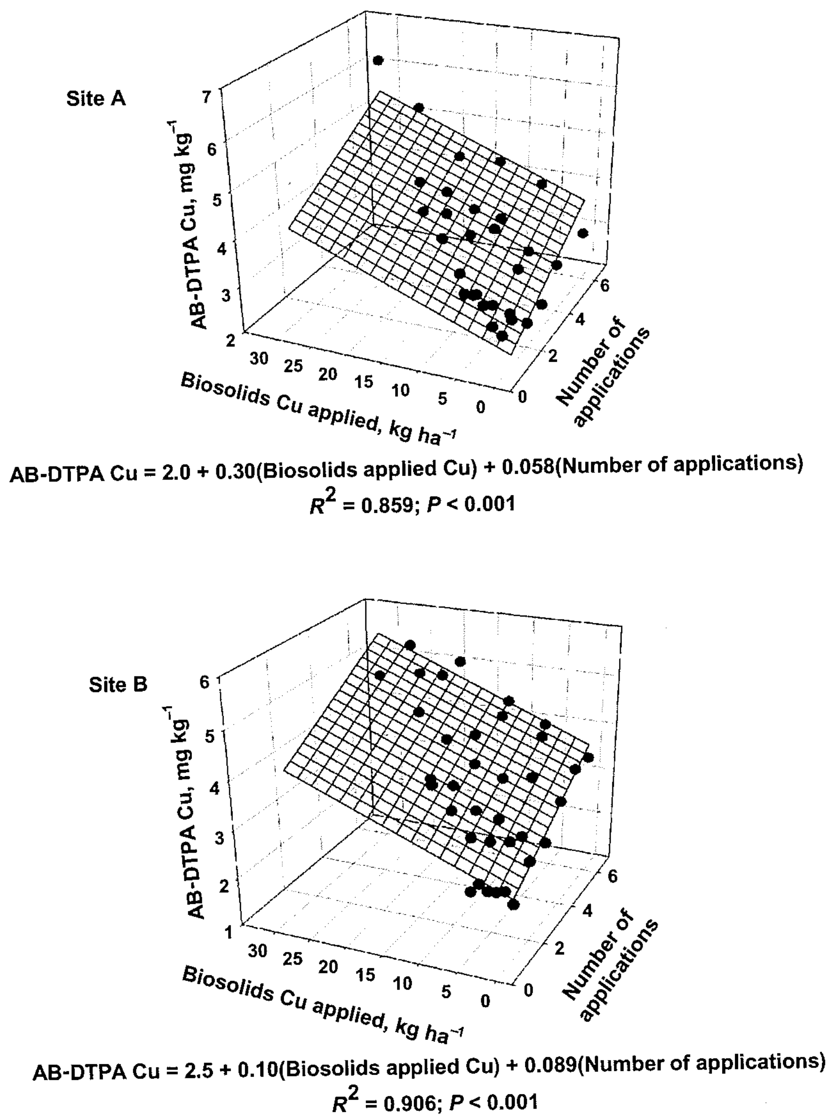


Fig. 4. Planar regression for AB-DTPA Cu versus amount of biosolids-borne Cu applied and number of biosolids applications at two dryland agroecosystem sites that received L/E biosolids.

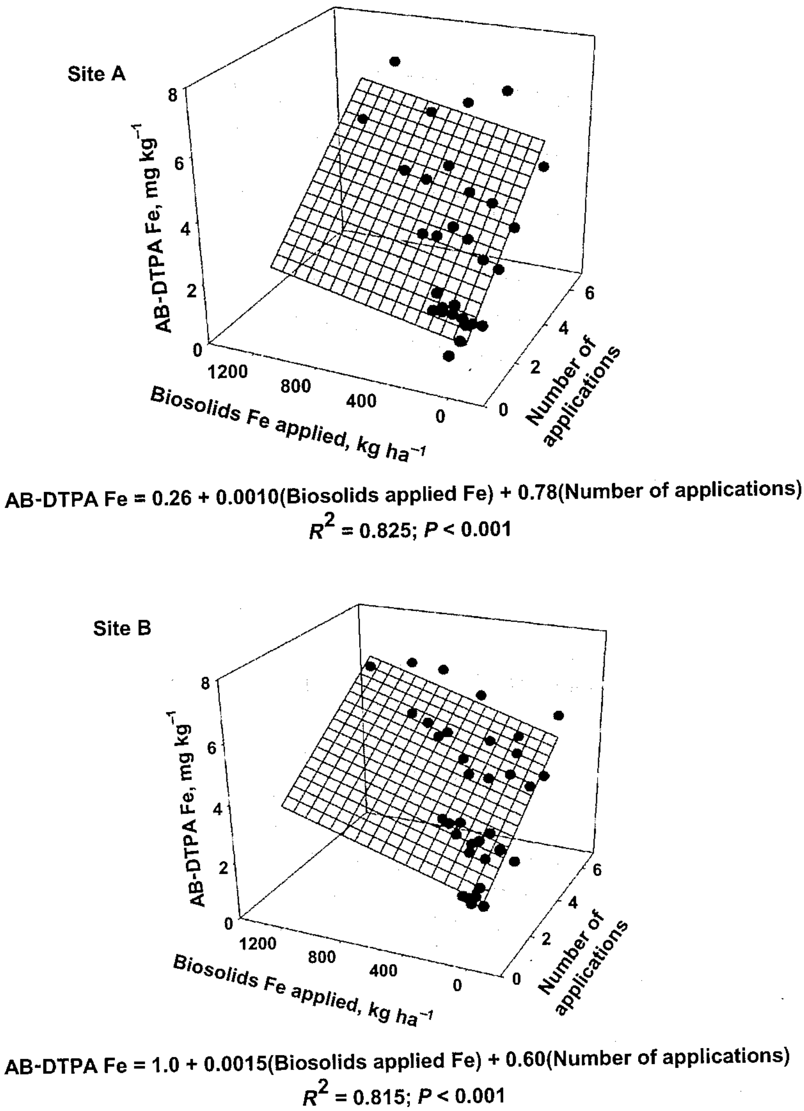


Fig. 5. Planar regression for AB-DTPA Fe versus amount of biosolids-borne Fe applied and number of biosolids applications at two dryland agroecosystem sites that received L/E biosolids.

(Mortvedt and Westfall, 2004). Table 5 provides the estimated amount of biosolids Zn needed for six continuous versus a single application to obtain adequate soil levels. Six applications required 1.4 and 1.9 times less biosolids-borne Zn to achieve the same estimated level of available Zn at Site A and Site B, respectively, compared with a single application.

We used the planar regression model shown in Fig. 3 to estimate biosolids P quantity required to reach 20 mg of AB-DTPA P kg^{-1}. This P concentration is considered high when assessed for the Colorado P Risk Index (Sharkoff et al., 2006). Six applications required 1.6 times less biosolids-borne P at Site B (Table 5) than a single application.

For plant-available Fe, the regression models provided in Fig. 4 were used to find the quantity of biosolids-borne Fe needed to raise the AB-DTPA Fe concentration to 10 mg kg^{-1}. This Fe concentration is considered adequate for Colorado soils (Mortvedt and Westfall, 2004). Table 5 provides the amount of biosolids Fe needed for six continuous versus a single application to obtain adequate soil levels. Six applications required 1.8 and 1.6 times less biosolids-borne

Fe at Site A and Site B, respectively, compared with a single application.

The Zn, P, and Fe estimations in Table 5 imply that six continuous biosolids applications were more effective in elevating these plant-available elements as compared with a single application; therefore, we rejected our second hypothesis. Sommers et al. (1991) stated that total cumulative trace metal amounts were more important than the application sequence (e.g., multiple vs. single application). Our results for two sites with Weld loam soils indicate, however, that better predictability of AB-DTPA–extractable levels occurs if the number of applications is included as a dependent variable in regression models, along with cumulative trace metal addition. This approach is useful for biosolids managers because the Weld soil is a significant series in eastern Colorado comprising 3.4×10^5 ha (NRCS, 2007b). In fact, soils classified like the Weld (fine, smectitic, mesic Aridic Argiustolls) comprise 2.3×10^6 ha in 11 states (Table 6; NRCS, 2007b). Because we developed the regression models based on sampling the mollic epipedon (the surface 20 cm) of two Weld soils, similar responses in soil extractability of Zn, P, Fe, and Cu for the other 21 soil series listed in Table 6 may be expected.

We did not complete a comparison for Cu because adequacy or risk indices do not exist for Colorado soils. However, planar regression equations are presented for both sites in Fig. 5 to aid in future applications in predicting plant-available soil Cu concentrations.

From a biosolids management viewpoint, these results support single addition application because a soil-chemical mechanism exists that reduces nutrient lability compared with multiple continuous applications. In other words, smaller more frequent applications increase the chance of mobile phases moving out of the plow layer versus a single large application. We recommend that at individual locations, soil samples be analyzed for extractable nutrients and the information be fitted to regression analyses using Eq.(1−4), so that the best predictive model is developed.

A planar-regression approach for predicting soil nutrient lability in a dryland wheat agroecosystem amended with multiple biosolids additions proved superior to linear, quadratic, or exponential-rise-to-a-maximum models. The addition of the number of applications parameter helped account for the reaction of biosolids-borne Zn, P, and Cu with soil constituents that eventually lower the plant availability of these nutrients over time. The planar regression estimates, therefore, are more mechanistically correct than using models where soil lability is a function of only the amount of element added.

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