A Survey of Soil Attributes in North Dakota by Landscape Position

D. W. Franzen,* T. Nanna, and W. A. Norvell

ABSTRACT

Land surveys of soil attributes can provide valuable information on the geographic distribution of important soil attributes and summarize the levels found. Landscape position can have a major influence on soil attributes. Consideration of field landscape variables in selecting sampling locations and interpreting results, even in large-scale surveys, should help to reduce unexplained variability in many soil attributes. We report the results of a survey of selected soil attributes in agricultural fields across North Dakota at sites selected within each field by landscape position. Our objective was to determine if this sampling design might contribute to a better understanding of the distribution of soil attributes. Soils from two or three fields within each of the 53 counties of North Dakota were sampled in 1996. Within each field, three samples of surface soil (0–15 cm) were obtained. One sample was collected from an upland position, one from a slope, and one from a depression. Each field was georeferenced using a differentially corrected GPS receiver. The samples were analyzed for DTPA (diethylenetriaminepentaacetic acid)-extractable Cu, Zn, and Cd; water soluble B and Se; and soil pH. Mapping and analysis showed distinct regional patterns of all soil factors. Some soil attributes, including pH and extractable Zn, Cu, and Cd, exhibited a strong relationship to field landscape position, while soluble B and Se were less related. The results suggest that separating field sampling locations into upland, sloping, and depressional areas will reduce the confounding effects of field landscape position on larger-scale spatial trends in soil attributes.

Mapping is a powerful tool for understanding the geographic distribution of soil attributes at any scale. National maps help delineate regions that tend to have higher or lower levels of certain properties (Holmgren et al., 1993; White et al., 1997; Gustavsson et al., 2001). Within regions, states, or counties, smaller areas with specific characteristics can be more accurately delineated at an appropriate scale (Holmgren et al., 1993; Wu et al., 2000). Within agricultural fields, relatively small areas can be identified as having differing soil attributes or differing management needs (Franzen et al., 1998a; Wu et al., 2000). Whatever the geographic scale, there is always a smaller scale at which variability exists (Franzen and Berglund, 1998; Pierce and Nowak, 1999; Webster, 2000). Failure to understand sources of small-scale geographic variability simply increases the unexplained variability in data collected over larger geographic areas.

Within-field variability in soil characteristics is common. Soil P and K levels (Peck and Melsted, 1973; Wollenhaupt et al., 1994; Franzen and Peck, 1995a), soil pH (Franzen and Peck, 1995b), soil organic C (Bhatti et al., 1991), chloride and Zn (Franzen et al., 1998b), and soil nitrate (Franzen et al., 1998a) have all been found to vary spatially within farm fields. Knowledge of within-field variability in attributes contributes to more effective agricultural soil management and assists also with the design of efficient strategies for studying the distribution of soil properties over larger areas. There is substantial evidence that within agricultural fields, the plant nutrients and soil factors of interest in a general soil survey of North Dakota might be related to landscape position. Copper, Zn, B, and Cd accumulate in organic matter (Stevenson, 1991), while soil pH of the region (Knuteson et al., 1989) and Se and Cd availability are related to some degree by hydrology, which in turn is related often to landscape position (Ruhe, 1960; Mikkelsen et al., 1989; Seiler, 1998; Wu et al., 2002). Previous site-specific soil sampling for plant nutrients revealed a tendency for several nutrients, including NO_3, Zn (Fig. 1), and chloride to be related to landscape position (Franzen et al., 1998a, 1998b).

The first objective of our survey was to measure and map the distribution of DTPA-extractable Zn, Cu, and Cd; water soluble B and Se; and pH in soils at three different landscape positions in fields across the state of North Dakota. Extractable forms of these trace elements measured by soil-testing methods were chosen because these measures are much better related to plant responses than are total concentrations of elements. Second, we wished to determine if the differences in these measured soil characteristics in samples from upland, sloping, and depressional locations within the field landscape were significant and sufficiently large to justify including landscape-based sampling in statewide surveys of soil characteristics.

MATERIALS AND METHODS

Soil samples were collected from each of the 53 counties in North Dakota during the summer of 1996. Samples were obtained from two to three cropped fields within each county (Fig. 2) Pasture and range fields were not included in the survey. Each field was georeferenced using a differentially corrected GPS receiver (Omnistar 7000 with satellite differential, Omnistar, Houston, TX), which recorded in latitude and longitude using the coordinate system WGS-84. Within each field, separate samples were collected from a typical upland, sloping, and depressional location. Each sample consisted of at least eight soil cores taken from a 0- to 15-cm depth with a 2.5 cm-diam. sample tube and was composited together in the field. No lubricant was used to obtain the samples. The subsample cores for each sample were obtained from an area of about 100 m^2 within each landscape position. The samples were then air-dried and ground to pass a 2-mm sieve. The samples were analyzed for soil pH (1:1 soil:water paste); DTPA-extractable Zn, Cu, and Cd (Lindsay and Norvell, 1978) with

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D.W. Franzen and T. Nanna, Dep. of Soil Sci., North Dakota State Univ., Fargo, ND 58105-5758; and W.A. Norvell, USDA-ARS, U.S. Plant, Soil, and Nutrition Lab., Ithaca, NY 14853. Received 10 Oct. 2005. *Corresponding author (david.franzen@ndsu.edu).

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677 S. Segoe Rd., Madison, WI 53711 USA

Abbreviations: DTPA, diethylenetriaminepentaacetic acid.

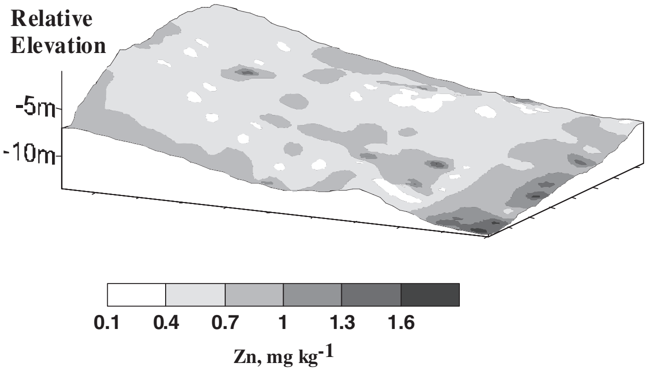

Fig. 1. Soil DTPA Zn levels from a 33-m grid sampling, layered over topography in a 16-ha field near Valley City, ND. Highest Zn levels are in depressions, and lowest levels are on ridge-tops. Data such as this at several site-specific sampling sites within the state were the inspiration for conducting a landscape-based state survey of soil factors.

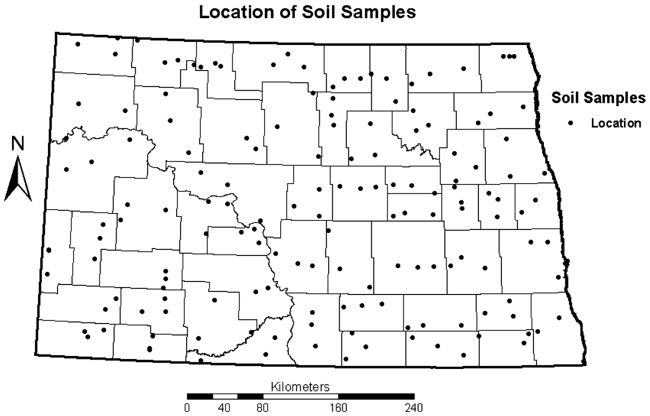

Fig. 2. Location of sampling sites in North Dakota. At least two, and most often three, sites within each of the state's counties were sampled. At each location, upland, slope, and depression landscape soil samples were obtained.

analysis by atomic absorption spectrophotometry for Zn and Cu and by inductively coupled argon plasma emission spectroscopy for Cd (ICP–AES; Fisons ARL Accuris, Ecublens, Switzerland); hot-water-soluble B (Berger and Truog, 1944) with analysis by colorimetry; and water soluble Se [1:1 soil: water extraction (Banuelos and Meek, 1990)] with detection by continuous-flow hydride generation atomic absorption spectrophotometry (Welsh et al., 1990; Wright and Stucynski, 1996).

Geostatistical analysis of soil data sets was conducted using GS$^+$ 5.1 (Gamma Design Software, Plainwell, MI). A spherical model was used to describe the relationship of semivariance to distance for all spatially dependent attributes. The parameters of the variogram model were optimized manually within the program by selecting the most favorable range, sill, and nugget values before creating the output file. The variograms selected were isotopic. Kriging estimates were generated with GS$^+$ 5.1 and mapped within Surfer 8.0 (Golden Software, Golden, CO). (For an excellent introduction to geostatistics and geostatistical vocabulary, see Isaaks and Srivastava, 1989.)

Maps were classified into equally distributed ranges, based on the ranges that were considered necessary to express meaningful patterns. The choice of classes is always somewhat subjective. The classes chosen tended to best reflect any relationship to major state soil groups.

RESULTS AND DISCUSSION

Concentrations of DTPA-extractable Zn, Cu, and Cd; water soluble B and Se; and pH in soils varied widely across North Dakota (Tables 1, 2, and 3) and usually differed significantly among landscape positions as shown by the comparisons of means and least significant differences in Table 4. There is a suggestion in some of the maps, such as B (Fig. 3), that some of the nutrient variability is due to soil differences (Omodt et al., 1968). The state is divided into three major soil regions. In the east, the Red River Valley stretches in a narrow 60-km strip from north to south across the state. In the southwest, soils are derived from unglaciated sediments from the Cretacious and Tertiary geologic periods, about 60 million years old. Between these two soil regions is a region of glacial till–derived soils. However, most of the soil factors and plant nutrients analyzed in this survey only roughly correspond to these major soils groups. Clearly there are other management and local soil differences in texture, organic matter, degree of erosion, historic use of manure, fertilization and fertilizer sources that must also be influencing individual soil analysis variation. The large nugget variance that is exhibited in most data sets (Tables 1–3) suggests that local factors are significant.

Soil pH varied from a low of 5.3 to a high of 8.5. Soils from depressional positions were more acidic than those from slopes or uplands. This is consistent with a dryland environment where carbonates are leached away in depressions but tend to accumulate in higher and drier parts of the landscape. The median pH of upland sites

Table 1. Classical and geostatistical summary of soil factors from soil obtained from upland landscape positions.

Statistic	pH	DTPA† Zn	DTPA Cu	B	DTPA Cd	Se
n	156	156	156	156	156	153
Mean	7.4	0.85 mg kg^{-1}	0.98 mg kg^{-1}	0.52 mg kg^{-1}	0.09 mg kg^{-1}	10.1 μg kg^{-1}
Median	7.8	0.53 mg kg^{-1}	0.96 mg kg^{-1}	0.40 mg kg^{-1}	0.08 mg kg^{-1}	9.38 μg kg^{-1}
Minimum	5.6	0.12 mg kg^{-1}	0.24 mg kg^{-1}	0.10 mg kg^{-1}	0.01 mg kg^{-1}	2.3 μg kg^{-1}
Maximum	8.5	7.72 mg kg^{-1}	2.41 mg kg^{-1}	1.80 mg kg^{-1}	0.29 mg kg^{-1}	31.1 μg kg^{-1}
Standard deviation	0.79	0.79 mg kg^{-1}	0.42 mg kg^{-1}	0.27 mg kg^{-1}	0.05 mg kg^{-1}	4.52 μg kg^{-1}
Skewness	−0.87	3.84	0.88	1.53	1.53	1.41
Kurtosis	−0.68	18.66	1.03	3.29	3.29	3.65
Variogram model	spherical	none	none	spherical	spherical	spherical
Nugget	0.38	–	–	0.02	0.001	11.4
Sill	0.64	–	–	0.06	0.0019	21.5
Nugget/sill	0.59	–	–	0.33	0.526	0.53
Range	62.4 km	–	–	72.0 km	48.0 km	160.3 km

† DTPA, diethylenetriaminepentaacetic acid.

Table 2. Classical and geostatistical summary of soil factors from soil obtained from slope landscape positions.

Statistic	pH	DTPA† Zn	DTPA Cu	B	DTPA Cd	Se
n	156	156	156	156	156	153
Mean	7.3	0.90 mg kg^{-1}	0.98 mg kg^{-1}	0.52 mg kg^{-1}	0.11 mg kg^{-1}	9.9 μg kg^{-1}
Median	7.6	0.72 mg kg^{-1}	0.89 mg kg^{-1}	0.40 mg kg^{-1}	0.11 mg kg^{-1}	9.76 μg kg^{-1}
Minimum	5.4	0.11 mg kg^{-1}	0.27 mg kg^{-1}	0.10 mg kg^{-1}	0.01 mg kg^{-1}	2.8 μg kg^{-1}
Maximum	8.5	4.8 mg kg^{-1}	2.67 mg kg^{-1}	1.80 mg kg^{-1}	0.30 mg kg^{-1}	22.6 μg kg^{-1}
Standard deviation	0.88	0.75 mg kg^{-1}	0.46 mg kg^{-1}	0.32 mg kg^{-1}	0.05 mg kg^{-1}	3.5 μg kg^{-1}
Skewness	−0.60	2.22	1.26	1.62	0.86	0.56
Kurtosis	−1.06	6.46	1.84	3.15	1.26	0.78
Variogram model	spherical	spherical	spherical	spherical	spherical	spherical
Nugget	0.30	0.17	0.13	0.058	0.0011	5.0
Sill	0.65	0.52	0.18	0.128	0.00215	12.7
Nugget/sill	0.46	0.33	0.72	0.45	0.512	0.394
Range	36.5 km	46.1 km	134.4 km	480 km	24.0 km	43.2 km

† DTPA, diethylenetriaminepentaacetic acid.

was 7.8 whereas the median of depressional sites was 7.0. The results illustrate the wide distribution of acidic soils in the state, and the differences among landscape positions suggest that compositing samples within a field could easily obscure the presence of smaller areas of more acidic soils in depressional positions. This oversight could easily have undesirable consequences related to the efficacy, phytotoxicity, and carryover potential of pH-dependent herbicides (Franzen and Zollinger, 1997) or overestimation of nutrient stresses. Soil pH at each landscape position was spatially variable across the state. The range distances for semivariograms of pH varied from 19 to 62 km, but the spatial relationships were not strong as suggested by the relatively large nugget-to-sill ratios.

Extractable Zn varied between 0.1 and 9.76 mg kg^{-1} and was significantly higher in soils from depressional positions. Depressions generally contain higher organic matter than other landscape positions and so would be expected to be higher in Zn. In uplands and slopes, the mean and median concentrations of Zn were below the critical level of 1 mg kg^{-1}, used in North Dakota as a basis for recommending Zn fertilizer for sensitive crops, including corn (*Zea mays* L.), dry edible bean (*Phaseolus vulgaris* L.), flax (*Linum usitatissimum* L.), and potato (*Solanum tuberosum* L.) (Franzen, 2003). Zinc concentrations were spatially related in soils from slopes or depressional positions but not evidently so in soils from uplands for which the nugget was indistinguishable from the sill in the variogram model.

Extractable Cu varied from 0.24 to 4.5 mg kg^{-1}. As noted for Zn, concentrations of Cu in soils from depressional positions were significantly higher than from locations higher in the landscape, probably due to higher organic matter content. Some spring wheat (*Triticum aestivum* L.) responses to Cu fertilizer have been found in the state at DTPA Cu levels below 0.40 mg kg^{-1} (Franzen and McMullen, 1999). Concentrations of Cu were spatially related in soils from sloping and depressional positions but not in samples from uplands for which the nugget was indistinguishable from the sill.

Cadmium levels varied from 0.01 to 0.31 mg kg^{-1}. As with Zn and Cu, soils from depressional positions were significantly higher in extractable Cd. The increased Cd levels of depressions compared with other landscape positions might be the result of higher organic matter levels but may also be related to possible higher chloride levels due to internal water movement (Franzen et al., 1998b). Comparing these values to the relationship between durum wheat grain (a grain used for manufacture of pasta) and Cd found by Garrett et al. (2001) and Norvell et al. (2000) in a range of North Dakota soils suggests that some, perhaps much, of the durum grain produced on soil in depressional positions could exceed the concentration of 0.2 μg kg^{-1} being considered as a limit by the FAO/WHO Food Standards Program (CODEX Alimentarius Commission, 1999). On the other hand, durum grain from the more extensive areas of uplands and slopes would seem much less likely to exceed this level. Further study of the effects of landscape position on Cd levels in crops is needed to clarify these relationships. Our results for Cd showed spatial dependency for soils from all landscape positions.

Boron levels varied from 0.1 to 1.8 mg kg^{-1}. Concentrations were spatially dependent at all landscape positions. Differences among landscape positions were

Table 3. Classical and geostatistical summary of soil factors from soil obtained from depressional landscape positions.

Statistic	pH	DTPA Zn	DTPA Cu	B	DTPA Cd	Se
n	156	156	156	156	156	153
Mean	7.0	1.77 mg kg^{-1}	1.30 mg kg^{-1}	0.62 mg kg^{-1}	0.18 mg kg^{-1}	11.4 μg kg^{-1}
Median	7.0	1.49 mg kg^{-1}	1.11 mg kg^{-1}	0.50 mg kg^{-1}	0.17 mg kg^{-1}	11.2 μg kg^{-1}
Minimum	5.3	0.21 mg kg^{-1}	0.45 mg kg^{-1}	0.10 mg kg^{-1}	0.04 mg kg^{-1}	4.2 μg kg^{-1}
Maximum	8.4	9.76 mg kg^{-1}	4.50 mg kg^{-1}	1.80 mg kg^{-1}	0.31 mg kg^{-1}	17.6 μg kg^{-1}
Standard deviation	0.86	1.21 mg kg^{-1}	0.65 mg kg^{-1}	0.33 mg kg^{-1}	0.06 mg kg^{-1}	4.2 μg kg^{-1}
Skewness	−0.14	2.45	1.93	1.08	0.27	1.05
Kurtosis	−1.34	11.37	5.07	0.69	−0.31	2.02
Variogram model	spherical	spherical	spherical	spherical	spherical	spherical
Nugget	0.36	0.60	0.01	0.035	0.0027	2.0
Sill	0.61	1.38	0.34	0.077	0.0032	17.5
Nugget/sill	0.59	0.44	0.03	0.45	0.84	0.11
Range	19.2 km	28.8 km	9.6 km	28.8 km	28.8 km	30.7 km

Table 4. Mean levels of Cu, Zn, Cd, soil pH, B, and Se by landscape position from the North Dakota survey.

	Soil nutritional property					
Landscape position	**pH**	**Zn**	**Cu**	**B**	**Cd**	**Se**
		mg kg^{-1}				µg kg^{-1}
Upland	7.4	0.85	0.98	0.52	0.094	10.1
Slopes	7.3	0.90	0.98	0.52	0.110	9.9
Depressions	7.0	1.77	1.30	0.62	0.175	11.4
LSD 0.05	0.19	0.22	0.11	0.07	0.012	0.9

relatively small, with highest levels in depressions, probably because of higher organic matter content. Crop responses to B are uncommon in North Dakota, and B is not usually recommended. However, this practice may need to be reviewed because the wide range of soil B concentrations from this survey includes many low values that would trigger recommendations in other states. For example, in Wisconsin, critical levels of B range from 0.5 mg kg^{-1} for sands to 1.1 mg kg^{-1} in clay soils (Kelling et al., 1998). The pattern of B levels in the state is similar to the general soils map (Omodt et al., 1968). On the eastern edge of the state is the Red River Valley, characterized by deep, glacial-lake-bed-derived sediments. This area is highest in B. In the southwest are residual sediments from the Cretaceous and Tertiary geologic periods. This area of the state's oldest sediments tends to be lowest in B. The glacial till area in between contains a wide range of values, reflective of the variable nature of the often water-worked sediments that are the product of glacial melt.

Water extractable Se levels varied from 2.3 to 31.1 µg kg^{-1}. Little effect of landscape position was evident, although depressions tended to be higher than slopes. This might be due to more shallow water tables in depression where soluble Se might accumulate. None of the levels found in soils from this survey approach those that would cause Se in crops to reach levels toxic to humans or livestock (Jump and Sabey, 1989). However, some of the soils may contain enough available Se to result in a beneficial increase in the Se in food crops grown for human consumption (Hintze et al., 2001).

The spatial relationships exhibited by our soil data were often weak as shown by the relatively large nugget/sill ratios for variograms and by the absence of a detectable range distance for Zn or Cu in upland soils (Tables 1–3). The weakness in these spatial relations suggests that a great deal of variability existed at smaller spatial scales than could be detected at the low sampling density used in this survey. The range distances varied from a low of 9.6 km for Cu in depressional positions to a high of 480 km for B in sloping positions, but most range distances were less than 160 km.

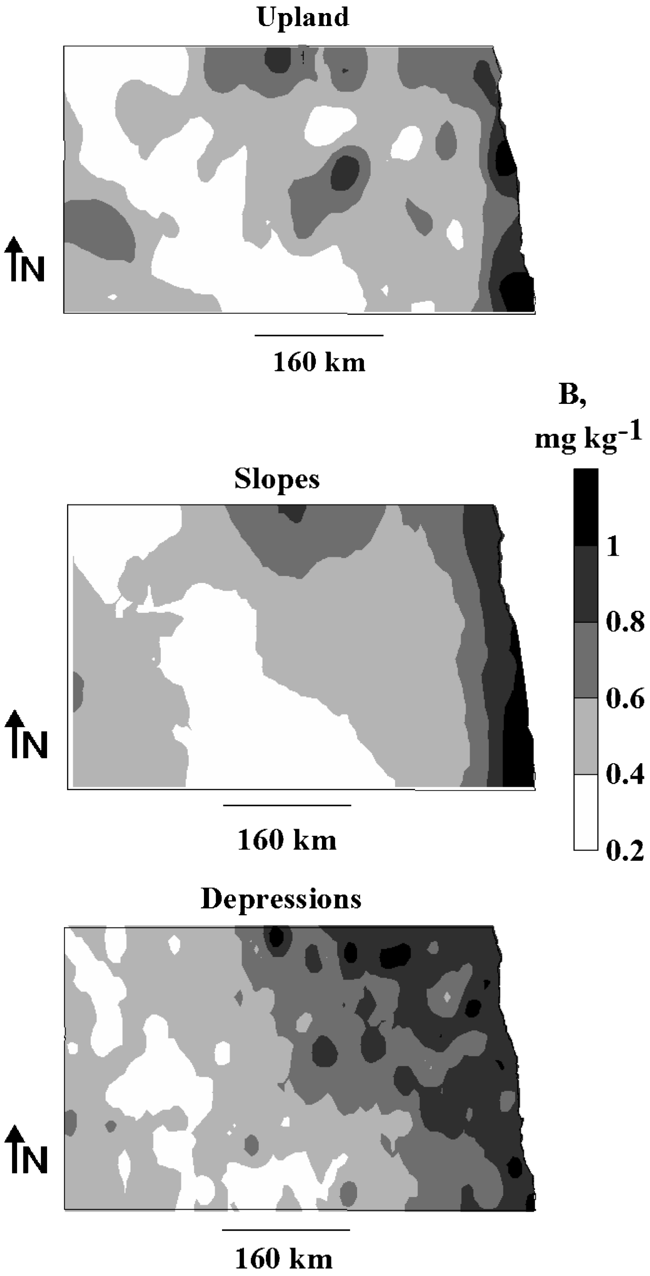

Fig. 3. Hot-water-soluble B levels in upland, slope, and depressional positions, North Dakota.

Figures 3 through 8 show maps of soil pH, Zn, Cu, B, Cd, and Se levels in North Dakota. The trends in soil pH across the state were similar for all landscape positions. The highest pH levels were found in the east, north-central, and far west (Fig. 6) where large areas within the range of 7.5 to 8 are common. In depressions, soils were less alkaline, but high-pH values from 7.5 to 8 were still common in the east. Acidic soils were found commonly from the south-central part of the state north to the Canadian border. Lowest pH levels were found in south-central North Dakota, in unglaciated residual sediments common to that area. While Fig. 6 displays major pH trends across the state, it is important to remember that is always necessary to test soils locally to determine the pH within individual fields or across a field landscape.

The trends in extractable soil Zn across the state were in many respects similar among uplands, slopes, and depressions even though the amounts generally increased from upper to lower landscape positions. The lowest concentrations for soils from each landscape position were found in the northwest and southwest, with extensive areas of upland and sloping land characterized as

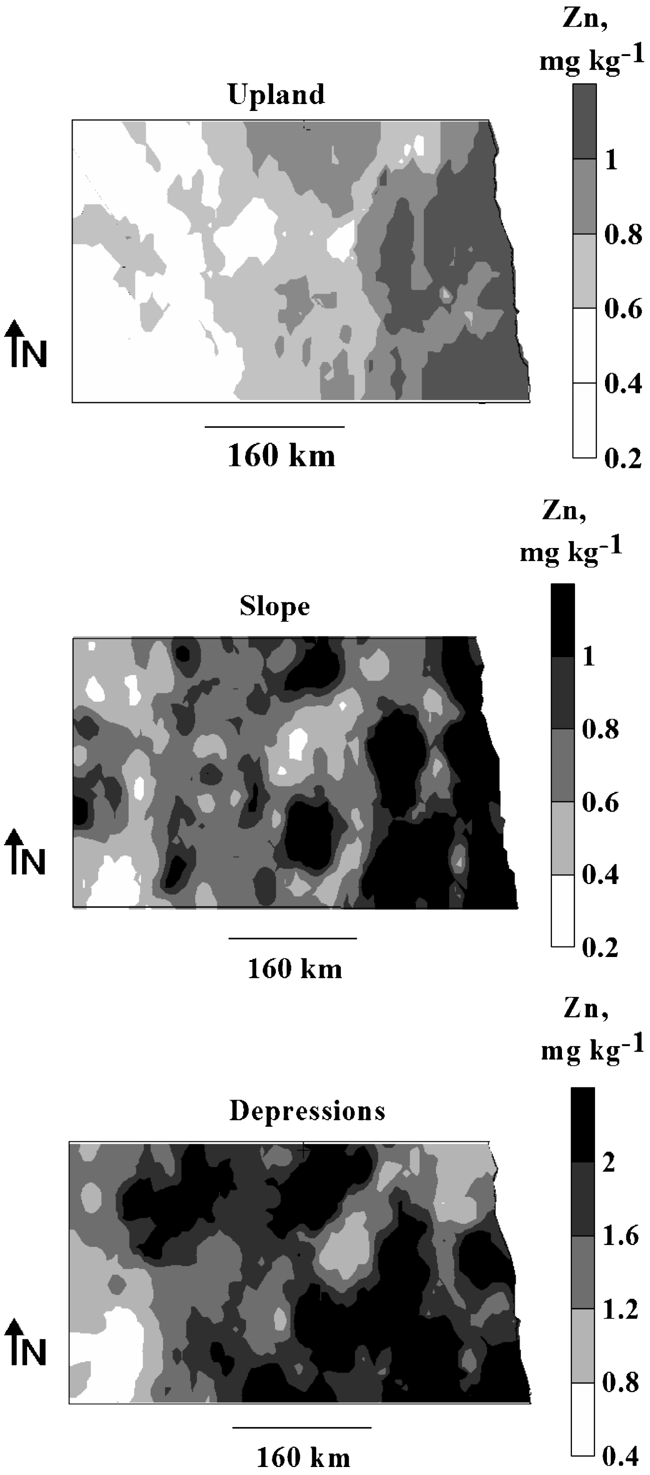

Fig. 4. DTPA Zn levels of upland, slope and depressional positions, North Dakota. Upland position Zn data set was not spatially related.

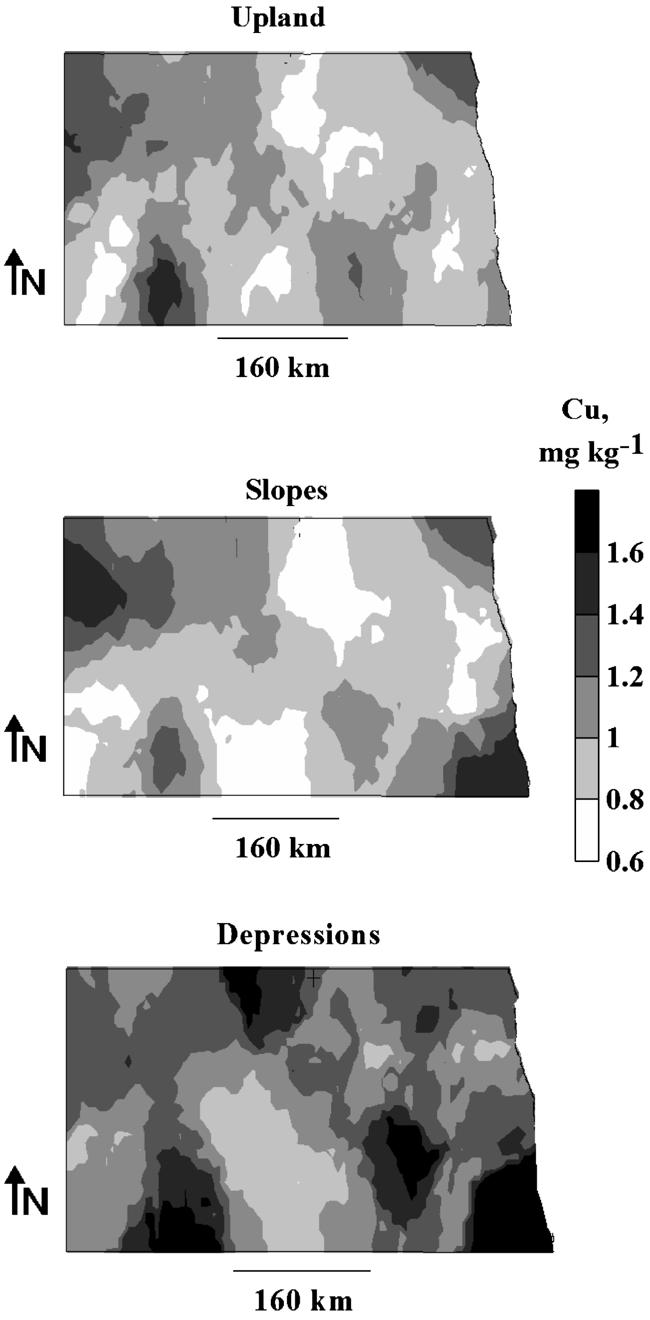

Fig. 5. DTPA Cu levels of upland, slope, and depressional positions, North Dakota. Upland position Cu data set was not spatially related.

supplying insufficient Zn for Zn-sensitive crops (<1 mg kg^{-1}). Soils in eastern North Dakota were relatively high in available Zn compared with soils in the west although soils from depressional positions contained relatively high concentrations of Zn in many parts of the state. Although the soils of the Red River Valley may be higher in native Zn than glacially or residually derived soils to the west, another possible reason for the higher Zn levels might be the greater historic acreage of dry edible bean, potato, and corn grown in the eastern part of the state (North Dakota Agric. Stat. Serv., 1997). These are crops that commonly receive applications of Zn fertilizer (Franzen, 2003).

The trends in Cu distribution, too, were similar in many respects for soils from upland, sloping, or depressional locations (Fig. 5). Soils in central North Dakota were relatively low in extractable Cu. Copper levels below 1 mg kg^{-1} were relatively common in soils of uplands and slopes but much less common in depressions. Copper

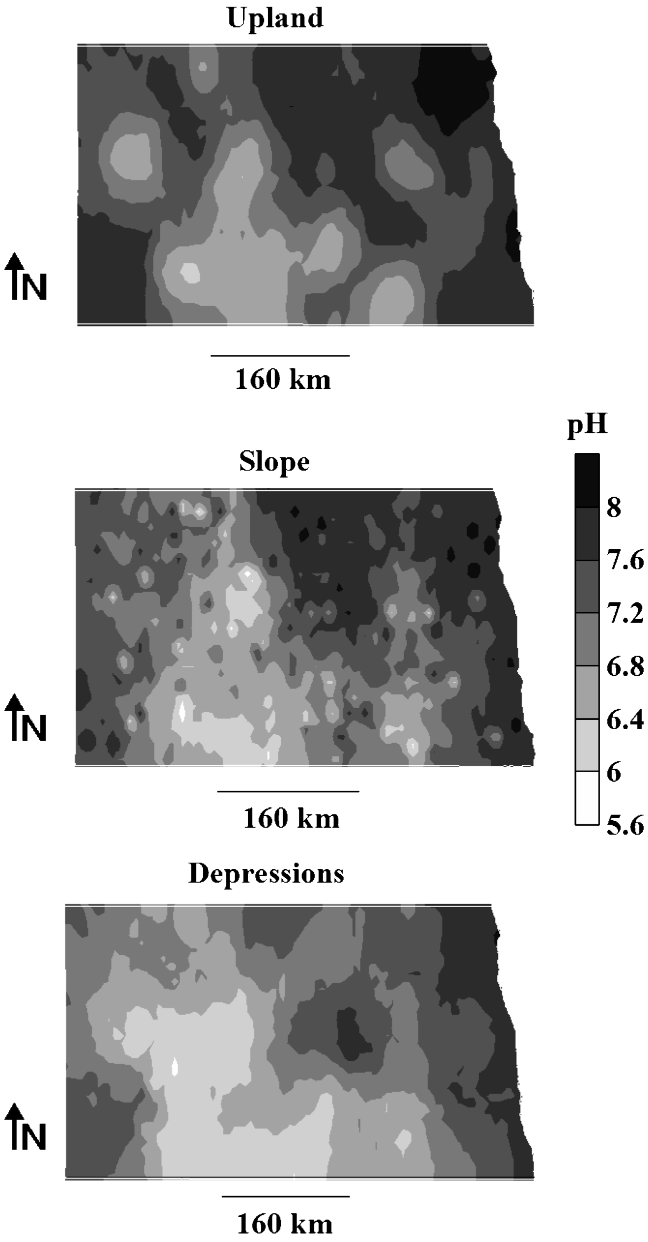

Fig. 6. Soil pH of upland, slope, and depressional positions in North Dakota.

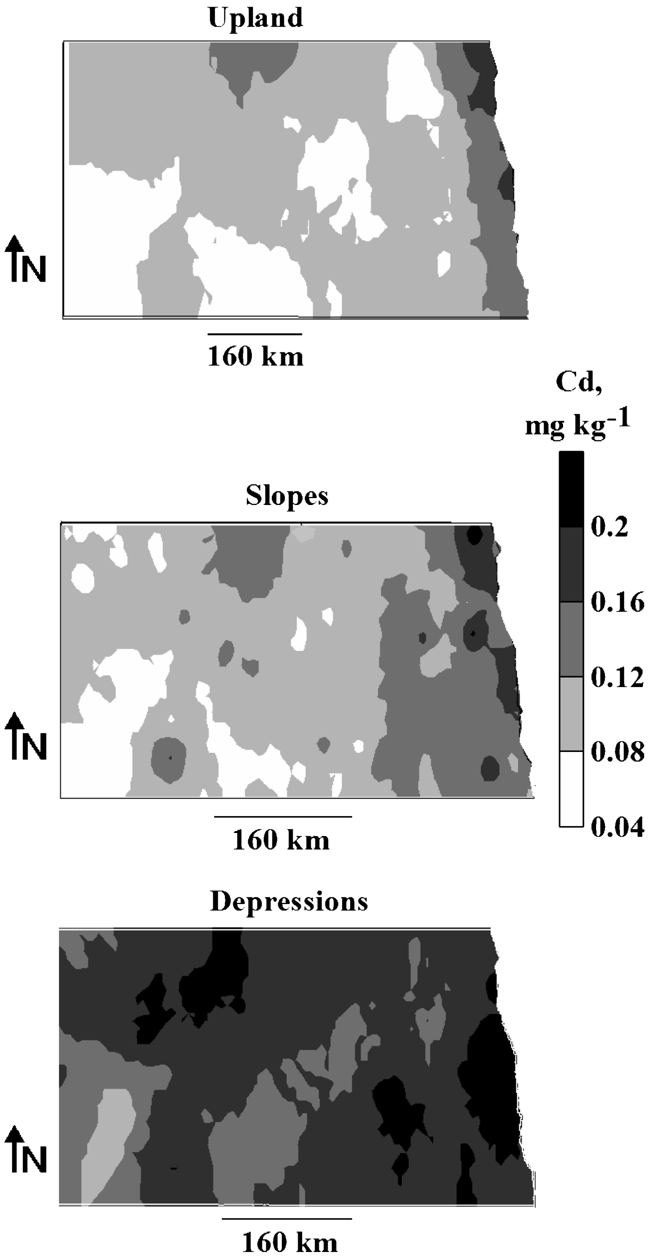

Fig. 7. DTPA Cd levels in upland, slope, and depressional positions, North Dakota.

levels below 0.5 mg kg^{-1}, where deficiency in crops might be considered as a possibility (Franzen and McMullen, 1999), were not common. Copper is only rarely applied as a fertilizer in the state. Variability within a region would more likely be due to native differences.

In upland samples, neither extractable Zn nor Cu was demonstrably spatially dependent even though the trends in Fig. 4 and 5 appear strong. This suggests that the range distance was less than could be detected at the low sampling density of this survey.

The distribution pattern for B in upland, sloping, and depressional soils was similar (Fig. 3). The highest levels of hot-water-soluble B were found in the eastern and north-central parts of the state. The lowest levels were found in the west, especially the southwest in the areas of Cretateous and Tertiary sediments. The highest levels of soluble B were usually found in depressional areas, suggesting that within-field assessments for B should separate depressions from uplands and slopes, especially in the eastern and northeastern parts of the state.

Extractable Cd concentrations in upland and sloping sites were notably lower than those in depressional positions (Fig. 7). Higher Cd levels were found in the east and north-central regions. The north-central portion of the state has previously been identified as having higher Cd levels than other regions, particularly due to glacial till that is relatively shallow in depth to Cd rich shale bedrock (Norvell et al., 2000). Lowest Cd levels were found in the southwest in the Cretaceous and Tertiary geologic period sediments. Previous research has

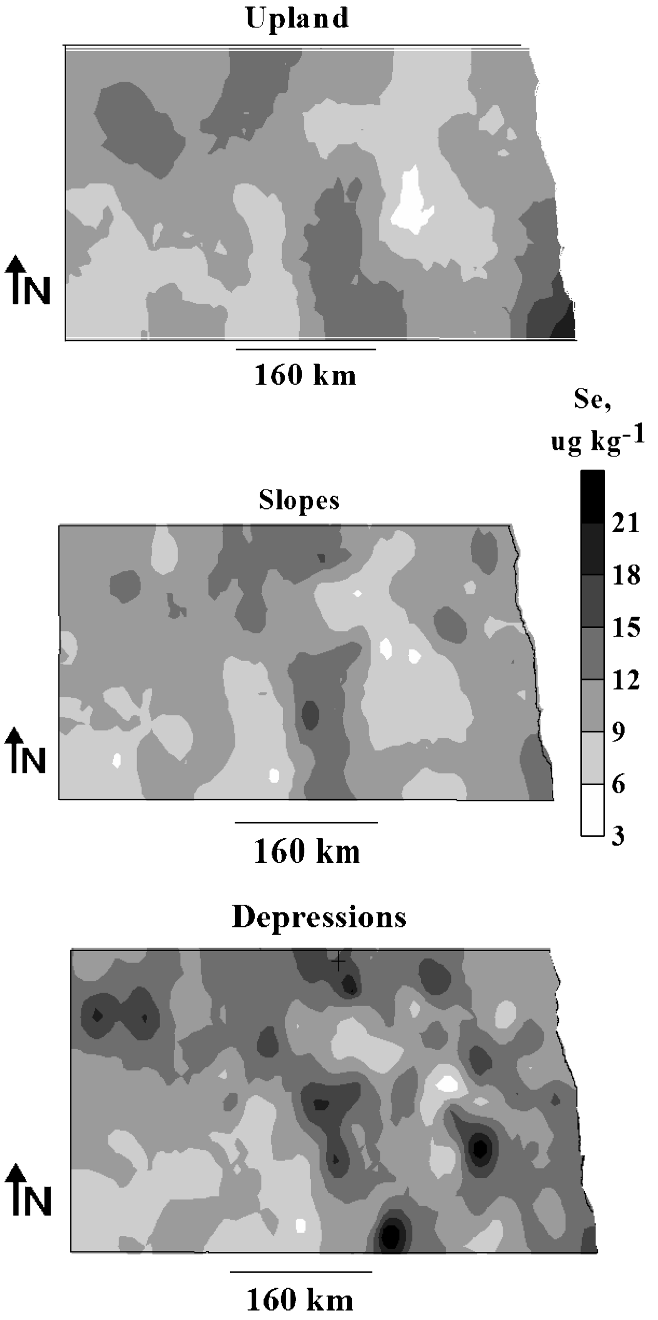

Fig. 8. Plant available Se levels in upland, slope, and depressional positions, North Dakota.

documented that Cd levels tend to be higher in areas with shallow depth to bedrock shale, particularly Pierre shale (Holmgren et al., 1993). That may explain the tendency for Cd levels to be higher in the north-central region and some areas of the northwest where the glacial till is sometimes shallow over shale.

No quantitative relationship between DTPA-extractable Cd in soil and Cd in crops has been established in North Dakota, but our results suggest that the potential for uptake of Cd from upland and sloping sites is greater in the eastern and north-central counties of the state. Greater potential for Cd uptake appears to exist in soils from depressional locations in all parts of the state, but less so for some of the soils in southwestern and central areas. In areas of elevated Cd-uptake potential, our results suggest that segregating and excluding grain harvested from depressional locations in the landscape would help to meet limits for Cd in grain exported to restrictive overseas markets. Other options to reduce Cd concentrations in seeds and grains include applying Zn fertilizers to soils with low available Zn and avoiding application of chloride-containing fertilizers (Li et al., 1994). In addition, avoiding fields with a history of manure applications, choosing fertilizer sources with low levels of Cd, and adding lime to acidic soils have also been suggested as means to reduce grain Cd in sensitive soil areas (Grant et al., 1999).

The distribution of water-soluble Se in soils from all landscape positions was generally similar (Fig. 8). The highest Se levels were found in the south-central, north-central, southeastern, and part of the northwest. Relatively low levels were found in the southwest and northeast. Soil from depressional locations tended to be higher in soluble Se than soil from higher in the landscape in all areas of the state except the southwest where little difference was found. Plant available Se is relatively mobile in soil and accumulates in water discharge zones in semiarid and arid regions (Parkin et al., 1990). With higher-than-normal rainfall, upland and sloped landscape positions would be expected to leach soluble constituents, such as Se, and levels would be reduced. Soil Se levels might also fluctuate between years depending on precipitation and Se leaching or accumulation due to internal water movement.

The Se maps in Fig. 8 are unlike those produced in other studies that specifically sought locations where plants might accumulate high levels of Se toxic to animals (Trelease and Beath, 1949; Boon, 1989). Maps of these potentially toxic areas may give the incorrect impression that much of the land within these zones is subject to a high levels of Se accumulation in plants. In reality, the locations in North Dakota with severe problems from Se accumulation are very limited in extent and are best described as localized sites with unusual characteristics, such as outcroppings of Se-rich shale or contamination from past U-mining activities. Our maps of water-soluble Se levels do not suggest the presence of Se levels that would result in any concern over high Se concentrations in cropped soils.

The results of this study suggest that future surveys of soil attributes should consider the landscapes from which samples will be obtained, perhaps by sampling and separately evaluating soils from differing major landscape units or by specifying a consistent landscape for sampling purposes. In this study, separating the sample locations into upland, slopes, and depressions helped to avoid confounding the large-scale trends in attributes across North Dakota with field-scale spatial variations that are related to landscape positions. Our results show that soils from depressional positions are generally lower in pH and higher in extractable forms of Cd, Cu, Zn, B, and Se than are soils from upland or sloping positions within the landscape.

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