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Irrigation Well Water in Nebraska

Nutrient Concentrations and Other Properties

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Key Words: *irrigation water, nutrient content, potassium, sulfur, boron, chloride, lime, electrical conductivity, sodium adsorption ratio*

Abbreviations

Water property abbreviations: B, boron; Ca, calcium; $CaCO_3$, calcium carbonate; Cl, chloride; CO_3, carbonate; Cu, copper; EC, electrical conductivity; Fe, iron; HCO_3, bicarbonate; K, potassium; Mg, magnesium; Mn, manganese; Mo, molybdenum; Na, sodium; N, nitrogen; NO_3, nitrate; NH_4 and NH_4-N, ammonium and ammonium-N; P, phosphorus; P_2O_5, phosphate; SAR, sodium adsorption ratio; SAR_{adj}, adjusted SAR; S, sulfur; TDS, estimated total dissolved solids; Zn, zinc.

Natural Resources Districts (NRD) abbreviations: CP, Central Platte; LB, Little Blue; LBB, Lower Big Blue; LC, Lewis and Clark; LE, Lower Elkhorn; LL, Lower Loup; LN, Lower Niobrara; LPN, Lower Platte North; LPS, Lower Platte South; LR, Lower Republican; MN, Middle Niobrara; MR, Middle Republican; NEM, Nemaha; NP, North Platte; PMR, Papio-Missouri River; SP, South Platte; TB, Tri-Basin; TP, Twin Platte; UBB, Upper Big Blue; UE, Upper Elkhorn; UL, Upper Loup; UNW, Upper Niobrara White; UR, Upper Republican.

Other abbreviations: ac-in, acre-inches; dS/m, deciSiemen per meter which is equal to millimho per centimeter (mmho/cm), both are units of EC; lb/ac, pounds per acre; meq/L, milliequivalents per liter; mg/meq, milligrams per milliequivalent; ppm, parts per million; <, less than; >, greater than.

Highlights

Water nutrient contents and other properties were surveyed across Nebraska in 2020 by sampling of water from 642 irrigation wells. Some highlights include:

- The amount of Ca, Mg, S, and Cl applied in irrigation exceeds removal in 200 bu/ac of corn grain for most wells;
- Irrigation supply exceeds corn grain harvest removal of B, K, Mn, and Mo for >15% of the wells;
- Irrigation supply of P, Zn, Cu, Fe, and B is generally very low but sufficient with some wells to be considered in nutrient management plans;
- The median level of nitrate N was 4.4 ppm but 25% of the wells had >10 ppm (the suitability limit for human consumption) of nitrate-N;
- >70% of the wells supply the agricultural lime equivalent in 10 ac-in needed to neutralize acidification by 200 lb of fertilizer-N;
- Nutrient and lime supply is relatively low for wells in the Sandhills and often relatively high for wells in river valleys of <100 ft depth;
- Only two of 642 (0.3%) wells had salinity levels of concern for corn and dry bean production;
- The sampled wells did not have excessive Na levels;
- Water properties vary widely between wells and an infrequent sampling of the water is needed for full optimization of nutrient and soil management; and
- Information on nutrients supplied through irrigation should be complemented by regular soil testing and the use of the recommended nutrient-management guidelines.

Introduction

Substantial amounts of some nutrients that are essential for crop growth are applied through irrigation in Nebraska. Crediting of irrigation-applied nitrate-nitrogen (NO_3-N) and sulfate-sulfur (SO_4-S) is advised in determining fertilizer nutrient rates (Shapiro et al., 2019). The irrigation-application of other essential nutrients is not directly credited but some may be indirectly credited when fertilizer use decisions are based on soil test results. This is also true for the liming effect of irrigation water. A survey of irrigation water properties was done in the 1960s for Nebraska (Culbertson et al., 1965). Wortmann (2019) revisited these results and found statewide median values (ppm) of 0.18 for phosphorus (P), 10.2 for potassium (K), 42.6 for calcium (Ca), 14.8 for magnesium (Mg), 12.9 for sulfur (S), 9.25 for chloride (Cl), and 0.11 for boron (B). Other nutrients were not considered. The results were reported on a county-basis with value ranges indicating much variation within as well as between counties.

There has been much expansion of irrigation since the 1960s, often with deeper wells and higher pumping rates, and more irrigation of sandy soil and hilly land. Irrigation practices have changed with centerpivot rather than furrow irrigation by far the dominant form of irrigation currently and irrigation scheduling is much better informed compared with the 1960s. These and other factors may have affected nutrient concentrations. Some counties were excluded from the 1960s survey. Information on the distribution of water concentrations of other essential nutrients is needed including for zinc (Zn), iron (Fe), copper (Cu), manganese (Mn), and molybdenum (Mo), as well as water quality properties including sodium adsorption ratio (SAR) and adjusted SAR (SARad), electrical conductivity (EC), total dissolved solids (TDS), pH, bicarbonate (HCO_3) concentration, hardness, and alkalinity. The objective of this survey was to generate a georeferenced database of 24 properties of water applied from irrigation wells in Nebraska, to map the results, and to relate this information to distribution across and within the 23 Natural Resources Districts (NRD) and five aquifer categories of Nebraska.

The procedures for sample collection and laboratory analyses, data analyses and interpretation, and mapping of results are reported in Appendix I, references are in Appendix II, and the quality control results are in Appendix III.

Results and Discussion

Many results are presented using box-and-whisker charts where 50% of the wells fall within the range of the box whereas the ranges for the upper and lower 25% are represented by the 'whisker' lines. The open circles represent outlying values. The X represents the mean (average) value and the vertical bar in the box represents the median value (the middle point of the number set). The information in box-and-whisker images is interpreted in terms of nutrient removed in the harvest of 200 bu of corn grain (Dobermann et al., 2010; Duarte et al., 2019) expecting the reader to adjust removal rates for other mean yield levels. The nutrient amounts applied are reported as pounds applied in 10 acre-inches which was calculated as the concentration (ppm) multiplied by 2.265. Map figures report concentration (e.g. ppm) values except for dS/m (or mmho/cm) for EC while pH and SARad which are unitless.

1. Distribution of Sampled Wells

The sampled wells generally represented the wells supplying center pivot irrigation but some areas could have had better coverage (the pivot distribution, county and NRD maps were accessed from the Nebraska Department of Natural Resources). The High Plains Aquifer is the major and most sampled aquifer of Nebraska (551 wells) but there was also significant sampling in the Paleovalley Aquifers (44 wells) and Maha (Dakota) Aquifer (47 wells).

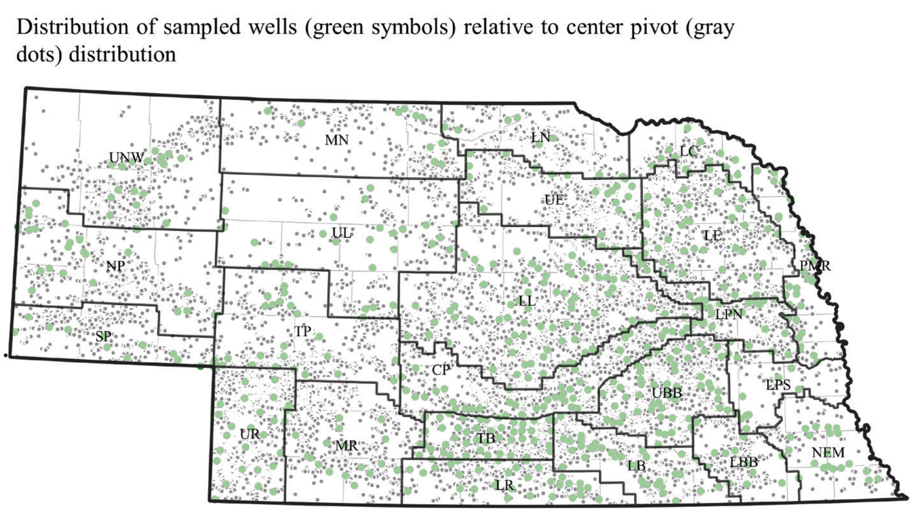

Fig. 1. Distribution of sampled wells (green symbols) relative to center pivot (gray dots) distribution.

2. Comparison of Aquifer Categories

Most water properties, on average, differed by aquifer categories but not P, Zn and Cu concentrations. Mean property values are generally high for the wells of the High Plains Aquifer of <100 ft depth outside of the Sandhills and low for wells in the Sandhills. The well-depth and pumping level are positively correlated with water pH but EC, adjusted SAR, and nutrient concentrations tended to be less with deeper wells and pumping levels except for Zn, Cu, and Mo. The median values are usually less than the means which are more affected by atypically high values compared with low values.

The current overall medians are lower compared with those of Culbertson et al. (1965), except for Ca and Mg, with 0.11 versus 0.18 ppm for P, 8.45 versus 10.2 ppm for K, 86.2 versus 42.6 ppm for Ca, 16.2 versus 14.8 ppm for Mg, 8.9 versus 12.9 ppm for S, 8.85 versus 9.25 ppm for Cl, and 0.05 versus 0.11 ppm for B. Greater well depth and more irrigation wells in the Sandhills may have contributed to these differences in the median values.

Table 1.

	High Plains <100 ft wells, n = 91		High Plains Sandhills, n = 57		High Plains, other, n = 415		Maha (Dakota), n = 46		Paleovalleys, n = 45	
Variable	**Mean**	**Median**	**Mean**	**Median**	**Mean**	**Median**	**Mean**	**Median**	**Mean**	**Median**
NO3	9.01a†	7.65	2.68b	1.60	7.64a	5.71	3.61b	1.70	3.05b	0.58
K	14.71a	12.43	6.28c	6.00	9.62b	8.56	8.20bc	7.00	5.61c	4.00
Ca	120a	112	32c	25	92b	85	120	113	113a	90
Mg	26.1a	21.8	5.3c	4.0	17.2b	15.1	28.6	27.0	25.9a	19.2
S	58.9a	38.0	2.8c	2.0	24.1c	11.7	41.3b	25.0	53.1ab	21.8
Cl	29.4a	22.5	2.3c	2.0	13.7b	7.2	11.2bc	6.0	16.6b	8.0
B	0.083b	0.072	0.021d	0.020	0.052c	0.046	0.092b	0.070	0.112a	0.066
Fe	0.222c	0.005	0.096d	0.005	0.019e	0.005	1.301a	0.020	0.344b	0.022
Mn	0.189b	0.005	0.069c	0.005	0.049c	0.005	0.387a	0.160	0.226ab	0.102
Cu	0.0076ab	0.0050	0.0070ab	0.0050	0.0069b	0.0050	0.0101a	0.0050	0.0063b	0.0050
Mo	0.0056b	0.0036	0.0019b	0.0010	0.0050b	0.0020	0.0051b	0.0030	0.0124a	0.0018
Na	61.0a	47.7	10.1d	8.0	30.7c	22.2	36.0bc	27.0	46.0b	34.6
SARadj	1.77a	1.53	0.44d	0.30	1.01c	0.78	1.08bc	0.90	1.42b	1.02
pH	7.67ab	7.65	7.74a	7.80	7.73a	7.74a	7.63b	7.60	7.70ab	7.72
TDS	595a	562	155d	128	422c	379	512b	473	502b	427
EC	0.99a	0.94	0.26d	0.21	0.70c	0.63	0.85b	0.79	0.85b	0.71
Hardness	410a	369	103c	79	301b	279	419a	388	392a	331
HCO3	355b	357	131d	106	314c	317	435a	419	362b	358

† Different letters within a row in the following indicate statistically significant differences between means.

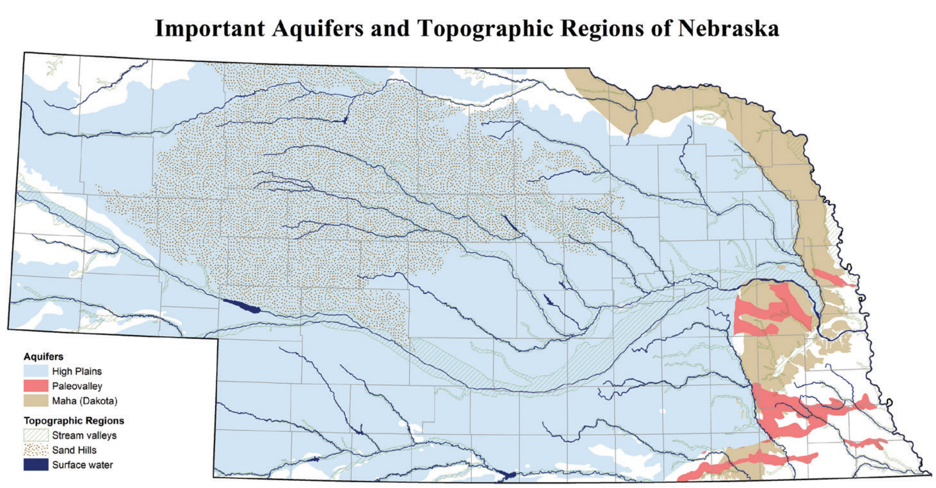

Fig. 2. Important aquifers and topographic regions of Nebraska.

3. Well Depth

The well depth is generally <100 ft in the CP and ≥ 300 ft in the LL, UE, UNW, and UR. The wells are relatively deep in the Sandhills. Many of the shallow wells are in unconfined alluvial aquifers of valleys with high water percolation rates, sometimes with furrow irrigation, with much potential for leaching of contaminants to the aquifer. However, a few alluvial wells were reported to have a clay or sandy clay layer which would slow percolation and leaching of nutrients.

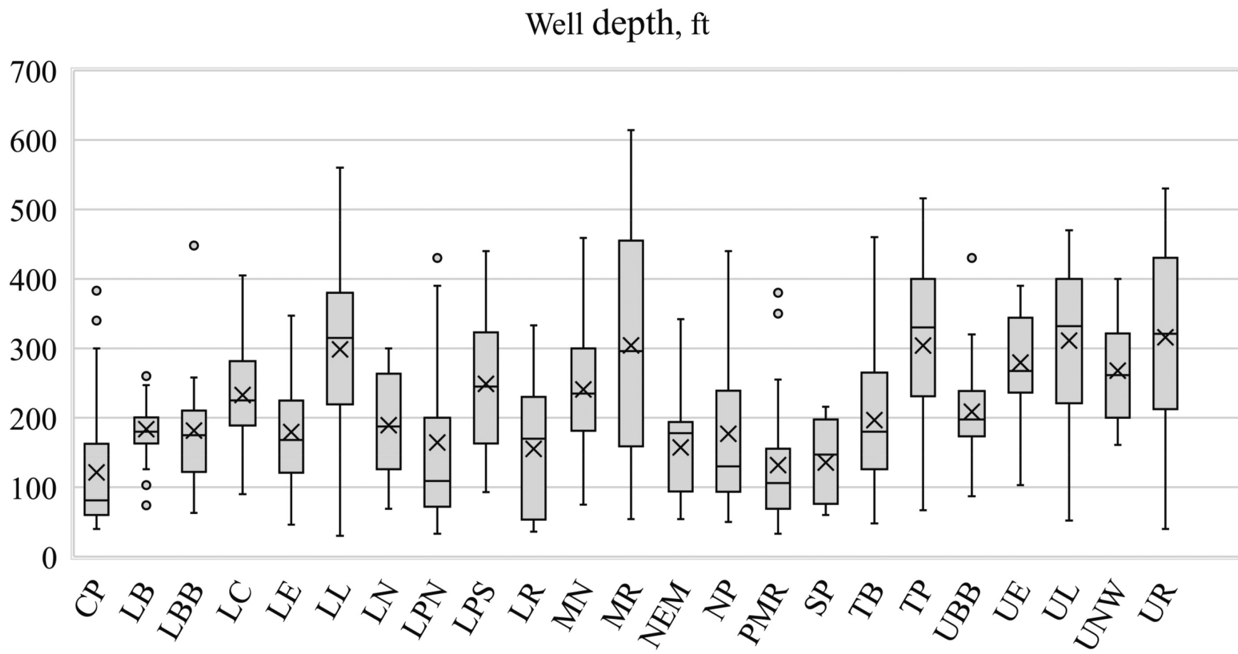

Fig. 3. Well depth, ft

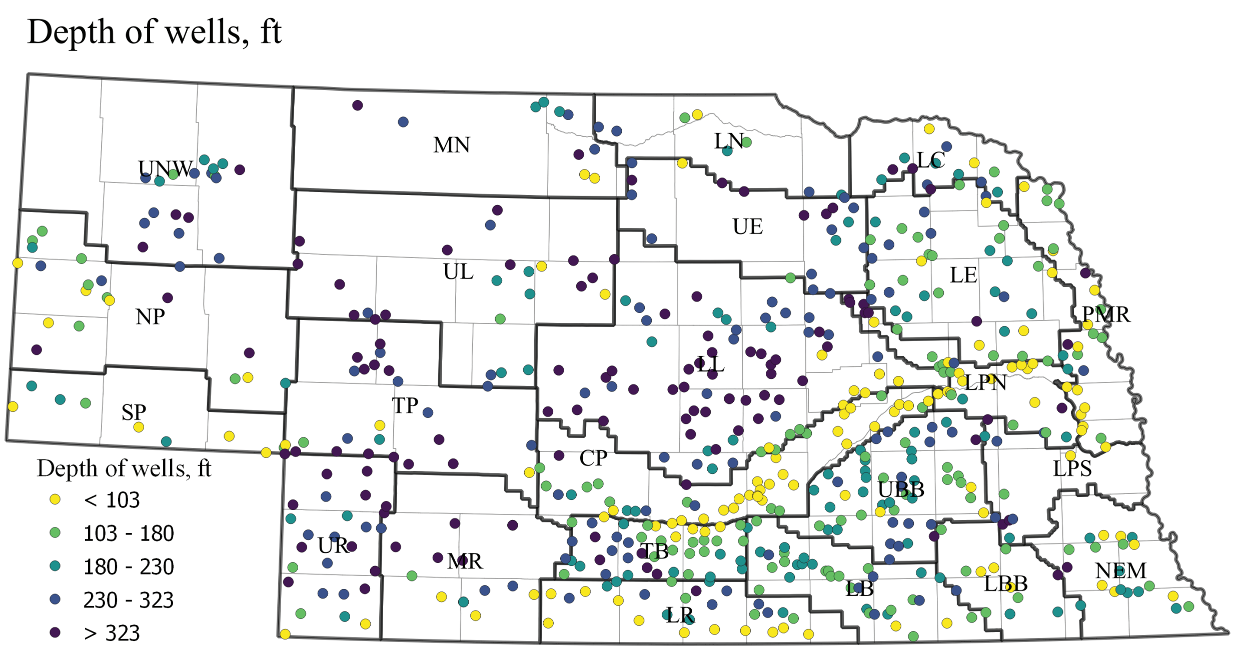

Fig. 4. Depth of wells, ft

4. Nitrogen (N)

The median level of NO_3-N in irrigation well water is 4.4 ppm (4.4 × 2.265 = 9.97 lb NO_3-N / 10 ac-in). Four wells supply >80 lb NO_3-N/10 ac-in. The median concentration of NO_3-N is highest for wells of the Great Plains Aquifer of <100 ft depth (6.05 ppm). The median concentrations are very low for wells in the Sandhills (2.50 ppm), the Maha (Dakota) Aquifer (1.60 ppm) and the Paleovalley Aquifers (0.40 ppm). Other wells of the Great Plains Aquifer had an intermediate median concentration of 5.10 ppm. The supply of NO_3-N is relatively great for CP, TB, UBB, and UE but low for NEM, PMR (especially in the Missouri River Valley), UL, UNW, and UR. About 25% of the sampled wells had a NO_3-N concentration ≥10 ppm, the legal drinking water limit.

The NH_4-N was also measured but levels are very low. The median values for NH_4-N are <0.1 ppm for all NRD, except for 0.2 ppm for NEM and 0.4 ppm for PMR. The levels are also low for wells of <100 ft depth in alluvial aquifers with vadose zones of high percolation rates. The overall median is 0.11 ppm with an overall mean of 0.28 lb NH_4-N/10 ac-in. More NH_4-N might have been expected as NH_4-N and NO_3-N concentrations in the saturated vadose were found to be similar in the Hastings area (Adams, 2020; Snow et al., 2020) whereas NH_4-N exceeded NO_3-N concentration in the Waverly area (Snow, 2019).

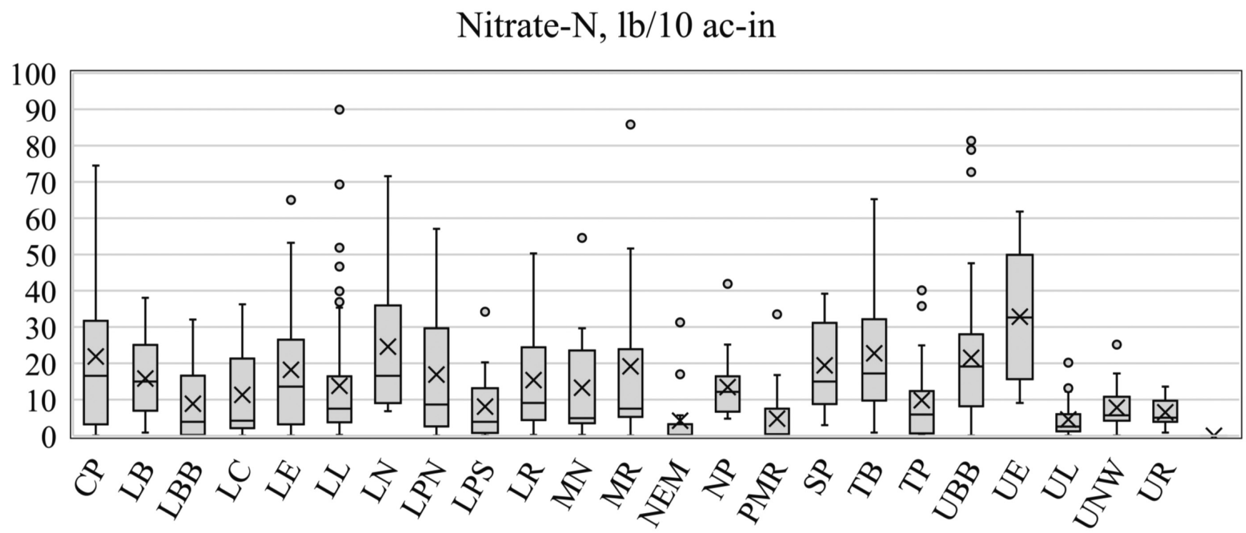

Fig. 5. Nitrate (N, lb/10 ac-in)

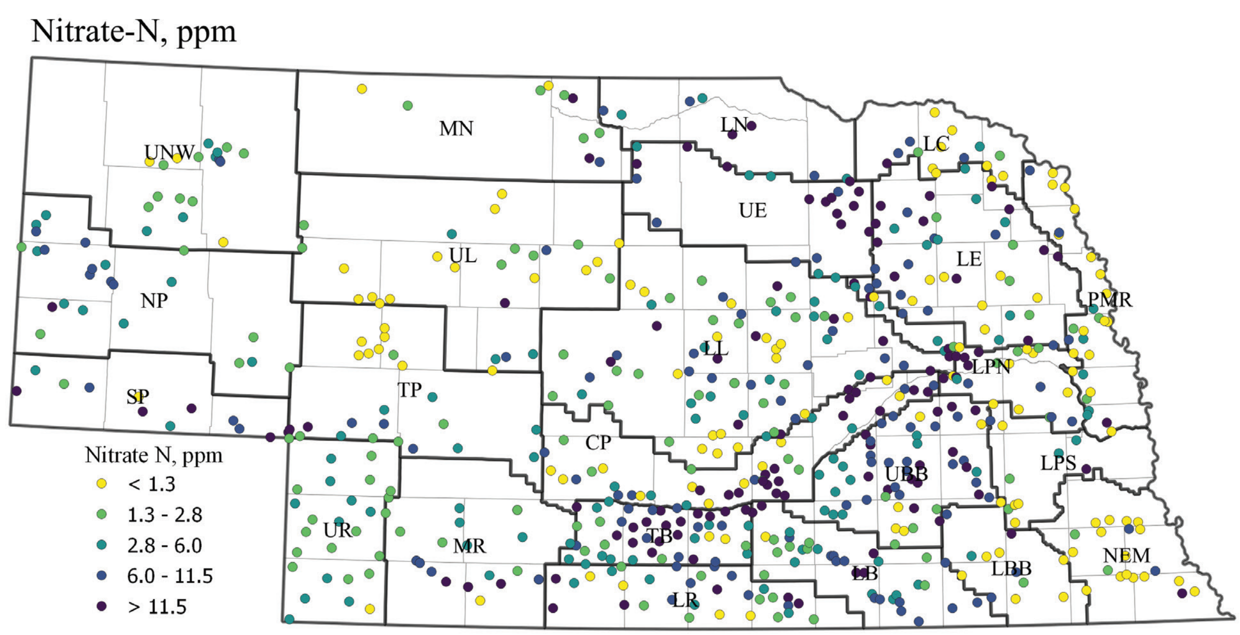

Fig. 6. Nitrate-N, ppm

5. Phosphorus (P)

The P concentration is above the reliable detection level (0.01 ppm) in water for 88.7% of the wells that were sampled. Irrigation water is a minor source of P with a mean supply of just 0.31 lb P (0.71 lb P_2O_5)/10 ac-in which is far less than removal in the harvest of 200 bu of corn grain. The aquifer and NRD means do not differ but P concentration is generally less in western compared with eastern Nebraska. Nine wells had outlier values that exceeded 1.2 lb P/10 ac-in.

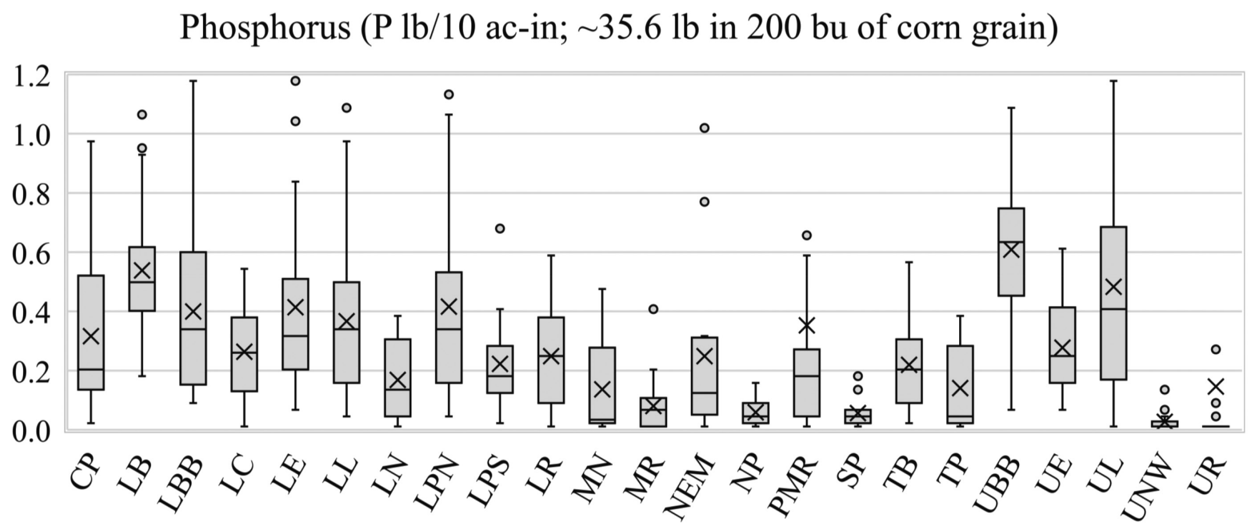

Fig. 7. Phosphorus (P, lb/10 ac-in; ~35.6 lb in 200 bu of corn grain)

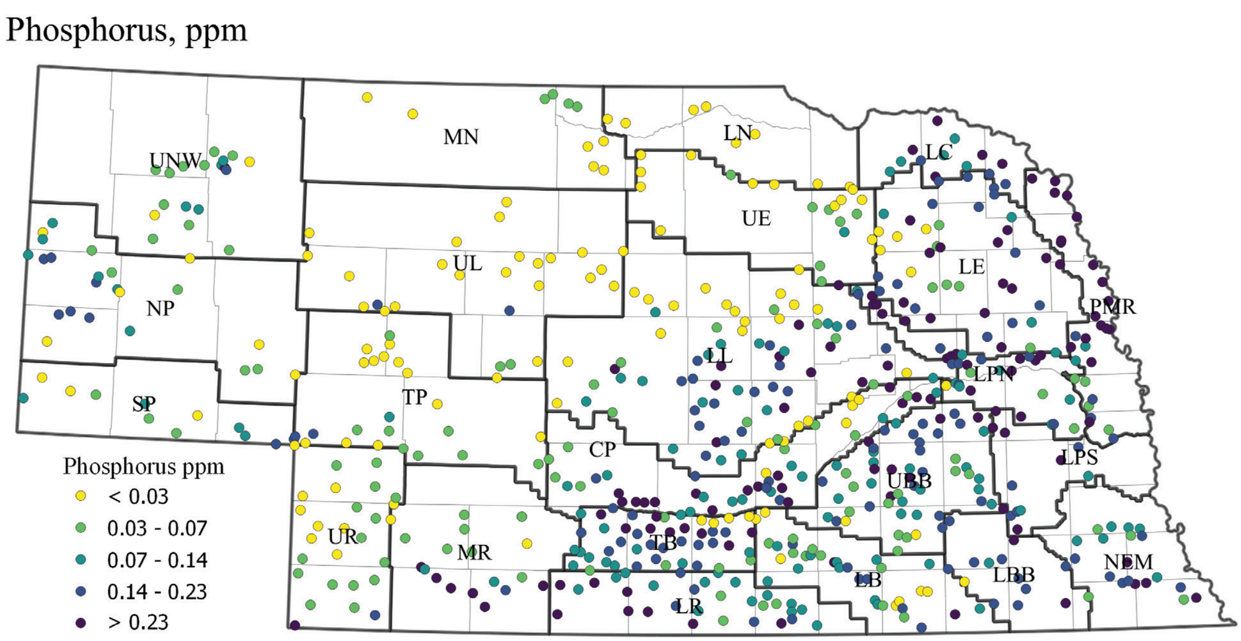

Fig. 8. Phosphorus, ppm

6. Potassium (K)

Irrigation can supply much of a crop's need for K and 20% of the sampled wells supply K in 10 ac-in that exceeds removal in the harvest of 200 bu of corn grain. Three wells supply >80 lb K in 10 ac-in. The irrigation K supply is not sufficient for most wells to replace K removal but does slow the rate of depletion for soil exchangeable K and reduces fertilizer-K requirements. The K concentrations are relatively high for wells of <100 ft in the Great Plains Aquifer and CP and MR, and relatively low in southeastern Nebraska and the Paleovalley Aquifers compared with elsewhere.

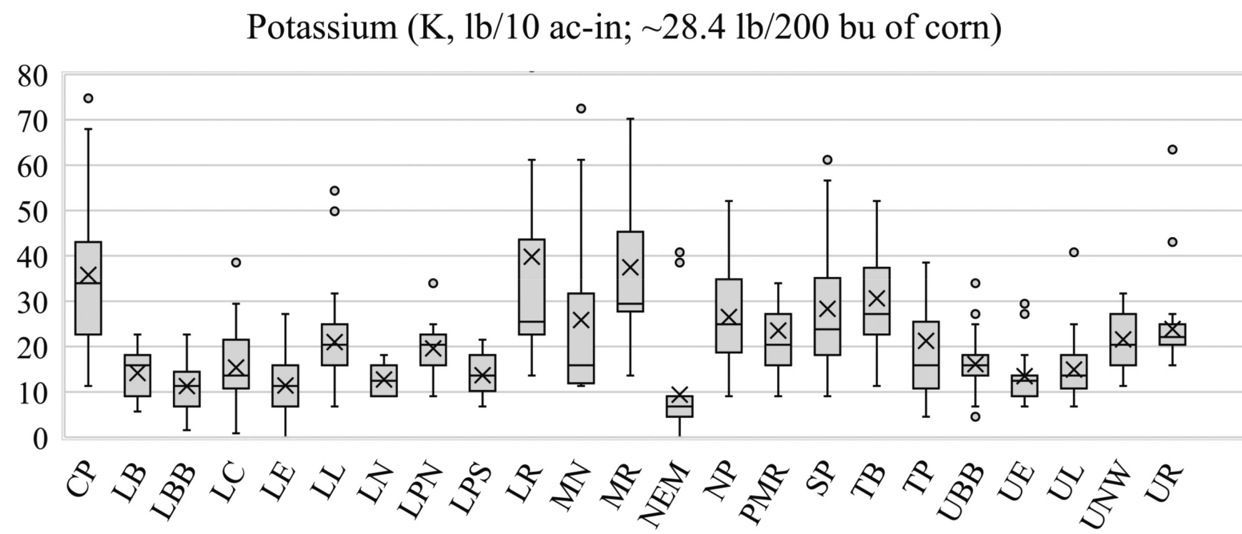

Fig. 9. Potassium (K, lb/10 ac-in; ~28.4 lb in 200 bu of corn)

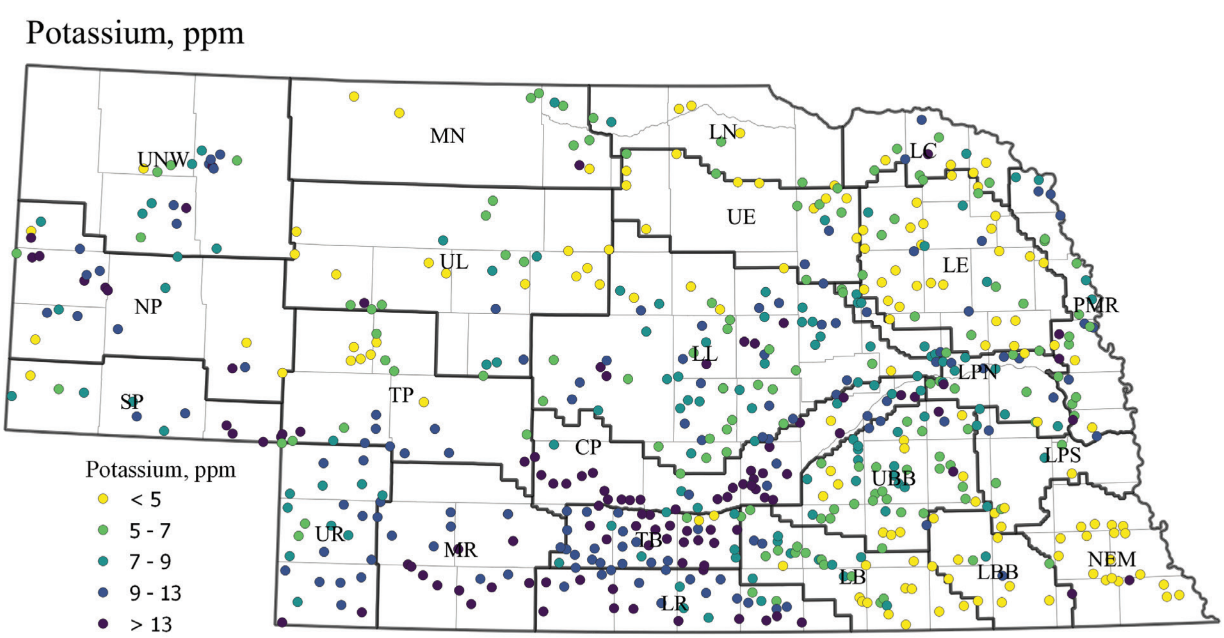

Fig. 10. Potassium, ppm

7. Calcium (Ca)

Irrigation supplies much more Ca in 10 ac-in than the Ca removal in 200 bu of corn grain. Eight wells supply >600 lb/10 ac-in. The Ca concentrations are relatively high for wells of <100 ft in the Great Plains Aquifer and in CP, PMR, and TB and relatively low in the Sandhills, LN, UL, and UR compared with other NRD. Concentrations tend to be higher in eastern and south-central compared with western Nebraska. Irrigation Ca may be valuable in preventing a surface and sub-soil build-up of exchangeable aluminum in the cation exchange complex of low pH soils. This may be especially important for sandy soils that are easily acidified with fertilizer-N application if the irrigation water has a low liming effect.

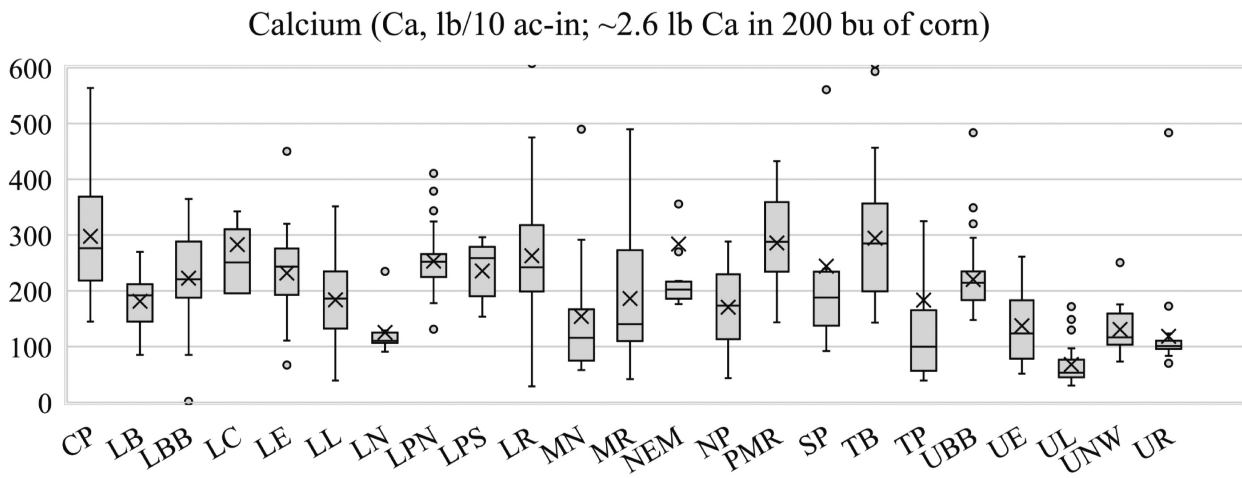

Fig. 11. Calcium (Ca, lb/10 ac-in; ~2.6 lb in 200 bu of corn)

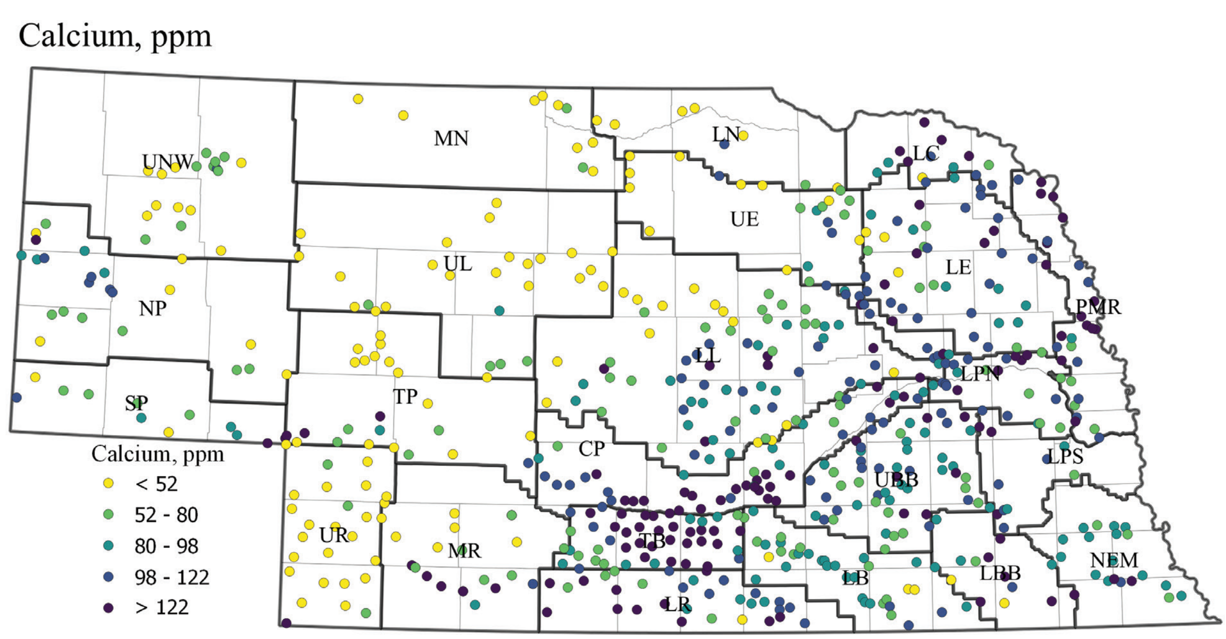

Fig. 12. Calcium, ppm

8. Magnesium (Mg)

Irrigation supplies much of a crop's need for Mg and 93.4% of the sampled wells supply Mg in 10 ac-in excess of removal in the harvest of 200 bu of corn grain. Eight wells supply >140 lb Mg/10 ac-in. The median Mg concentrations for high wells of <100 ft in the Great Plains Aquifer and in eastern and south-central Nebraska are high compared with farther north and west. The concentration tends to be relatively high in LC, CP and PMR, and relatively low in the Sandhills, UL and LN compared with other NRD.

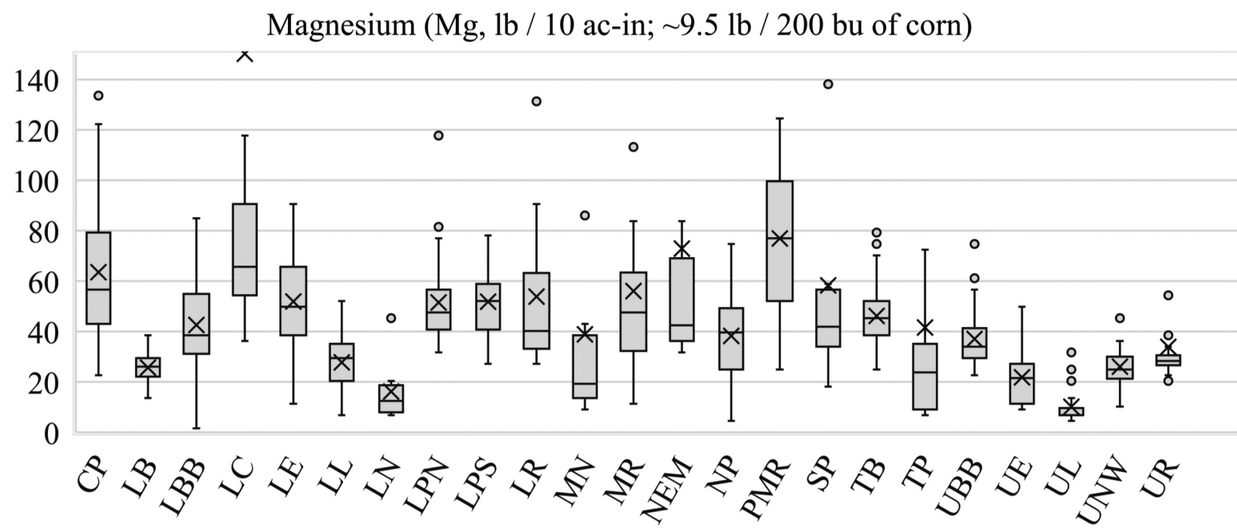

Fig. 13. Magnesium (Mg, lb/10 ac-in; ~9.5 lb in 200 bu of corn)

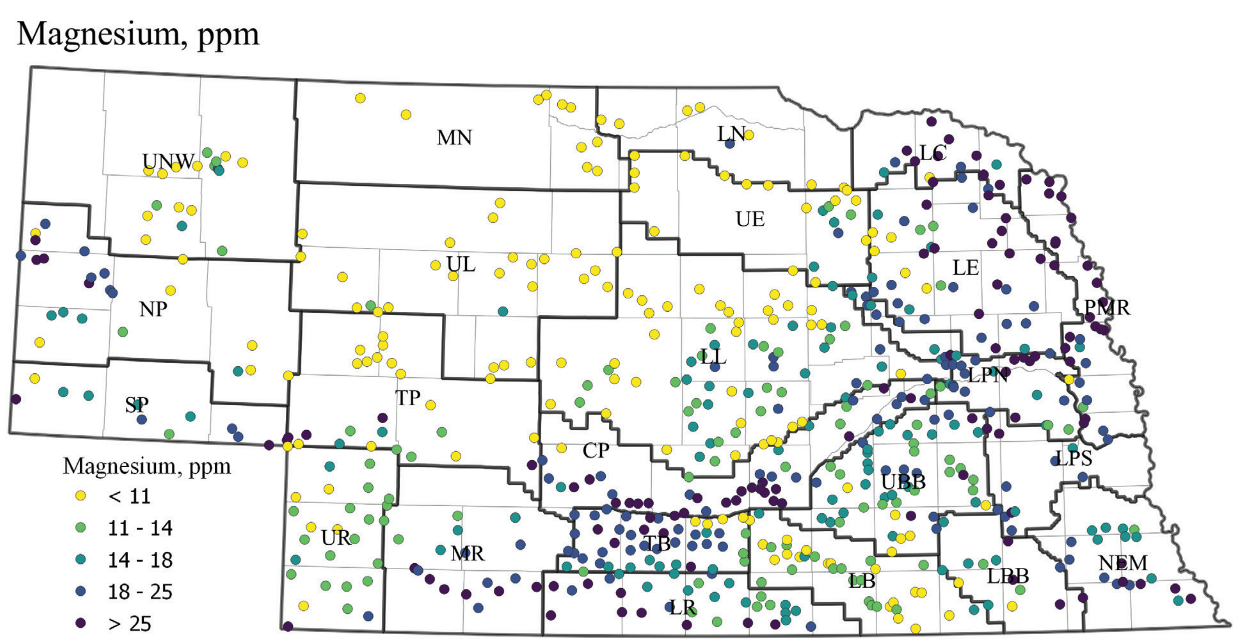

Fig. 14. Magnesium, ppm

9. Sulfur (S)

The S concentration is less than the reliable detection level (1 ppm) for only 1.5% of the sampled wells. Most wells supply abundant S with 72.9% of the wells supplying enough in 10 ac-in to exceed the S removed in grain harvest. The supply is >400 lb S in 10 ac-in for 19 wells. Irrigation water contains relatively more S for wells of <100 ft in the Great Plains Aquifer and in CP, NP and TB and less S in LB, LL, LN, MN, UE, UL, UNW, and UR compared with other NRD. The mean S concentration is less in the High Plains Aquifer for wells >100 ft depth, especially in the Sandhills, than in other aquifer categories.

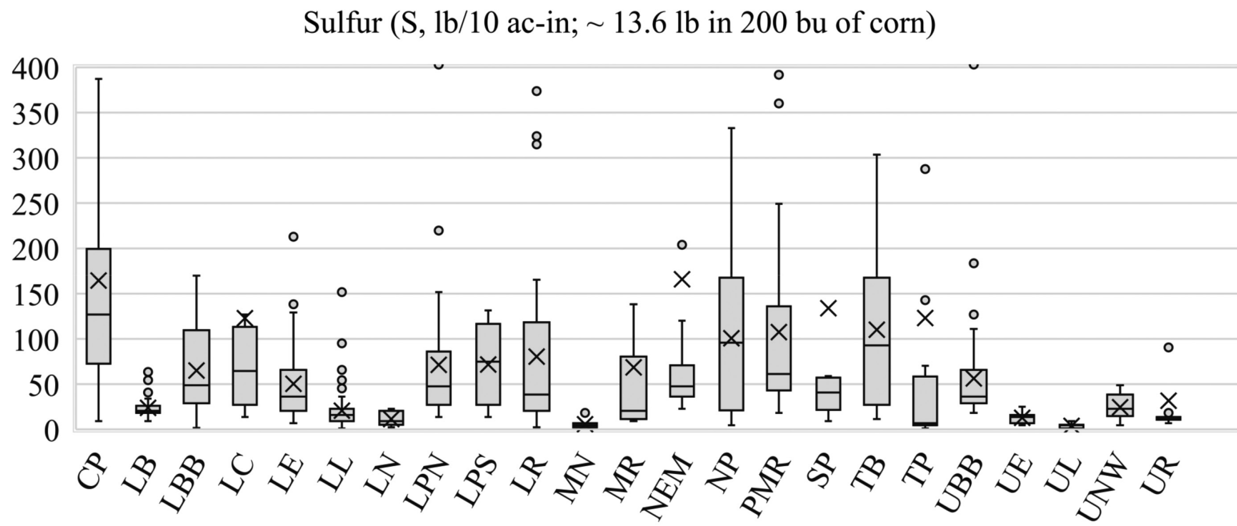

Fig. 15. Sulfur (S, lb/10 ac-in; ~13.6 lb in 200 bu of corn)

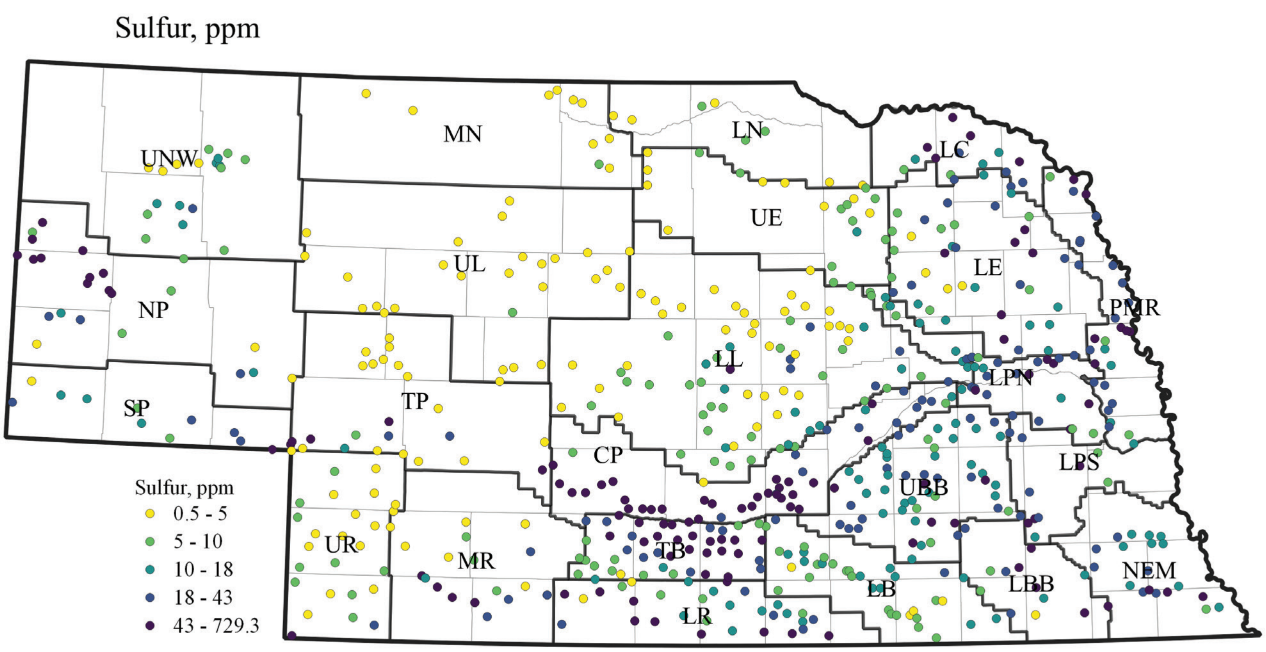

Fig. 16. Sulfur, ppm

10. Zinc (Zn)

The Zn concentration is below the reliable detection level (0.01 ppm) for 64.5% of the sampled wells. Only 4.2% of wells supply enough Zn in 10 ac-in to exceed the Zn typically removed in 200 bu of corn grain. Seven wells supply >1.0 lb Zn per 10 ac-in. Irrigation is more likely to replace Zn removed in grain harvest in LBB and LPS than in other NRD. Levels are also relatively high for wells in the Missouri River Valley.

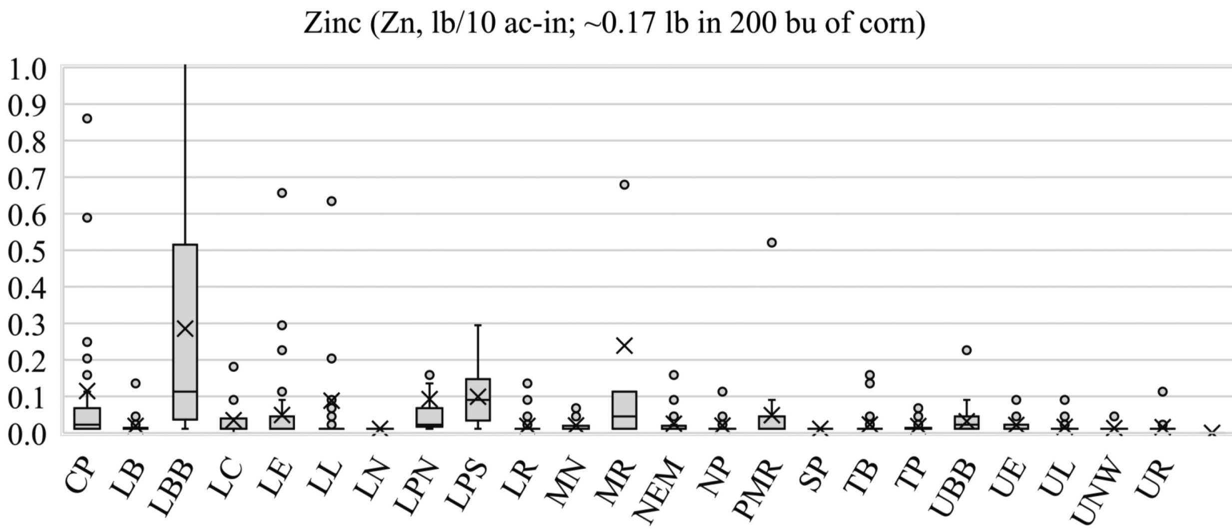

Fig. 17. Zinc (Zn, lb/10 ac-in; ~0.17 lb in 200 bu of corn)

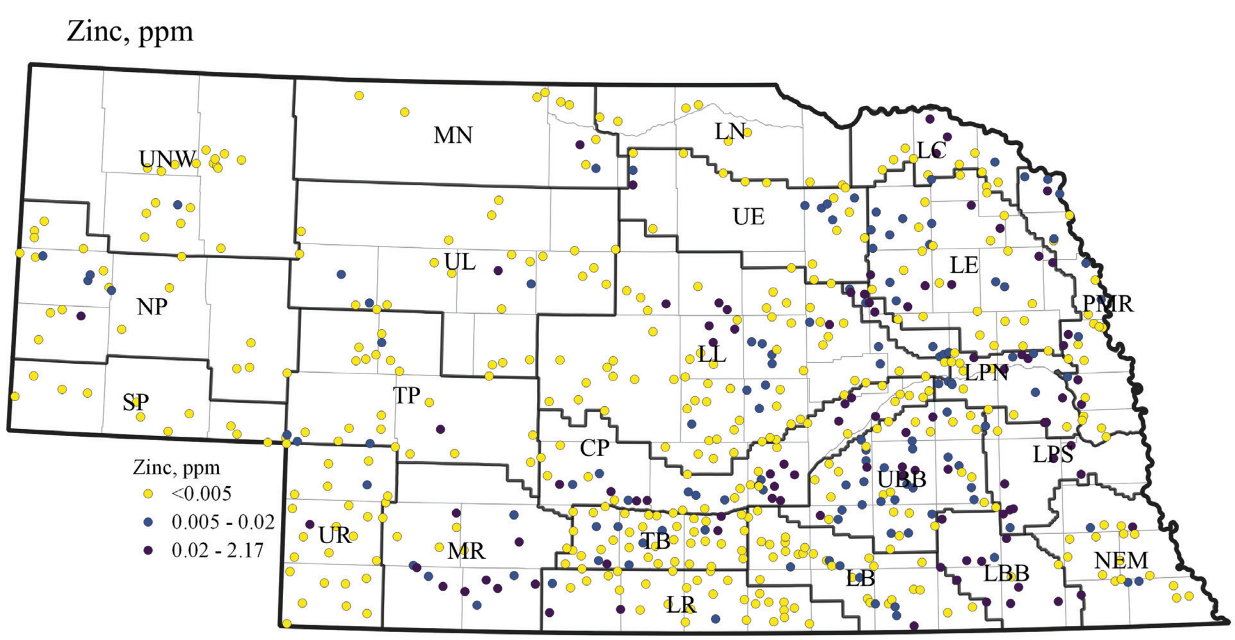

Fig. 18. Zinc, ppm

11. Iron (Fe)

The Fe concentration is below the reliable detectable level (0.01 ppm) for 77% of the sampled wells. Enough Fe is supplied in 10 ac-in by 8.9% of the wells to exceed the Fe typically removed in 200 bu of corn grain. Ten wells supply >2.0 lb Fe per 10 ac-in. Irrigation is more likely to replace Fe removed in grain harvest in NEM and PMR than in other NRD. Irrigation-Fe is not enough to treat Fe deficiency associated with some calcareous soils in the Platte River Valley and in northeastern and western Nebraska. There is a group of wells in Arthur, Grant, Hooker, and McPherson counties and wells in the Missouri River Valley with relatively high Fe concentration.

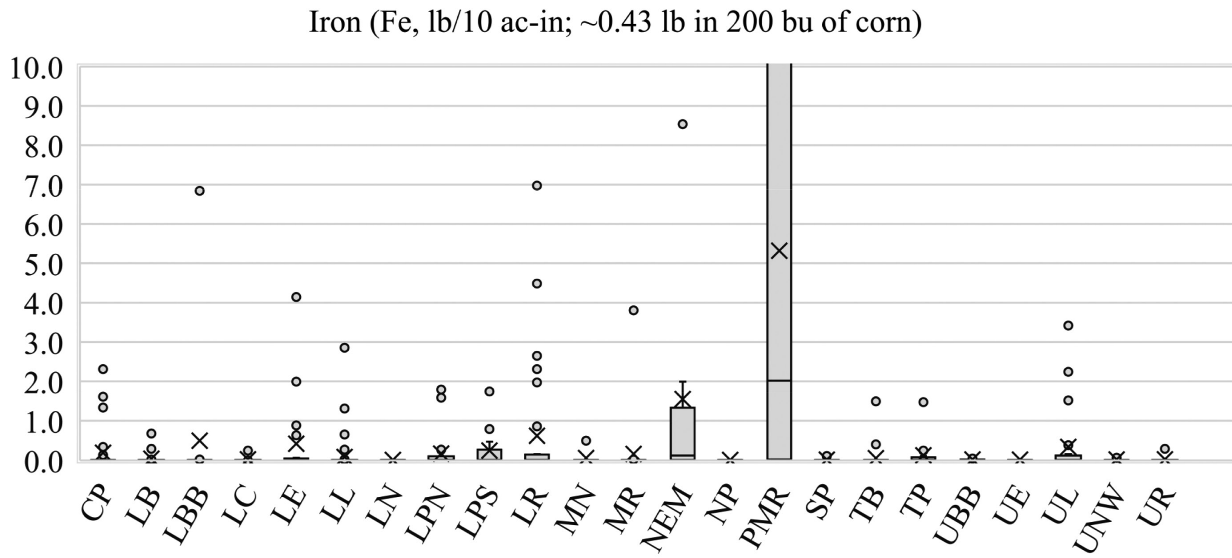

Fig. 19. Iron (Fe, lb/10 ac-in; ~0.43 lb in 200 bu of corn)

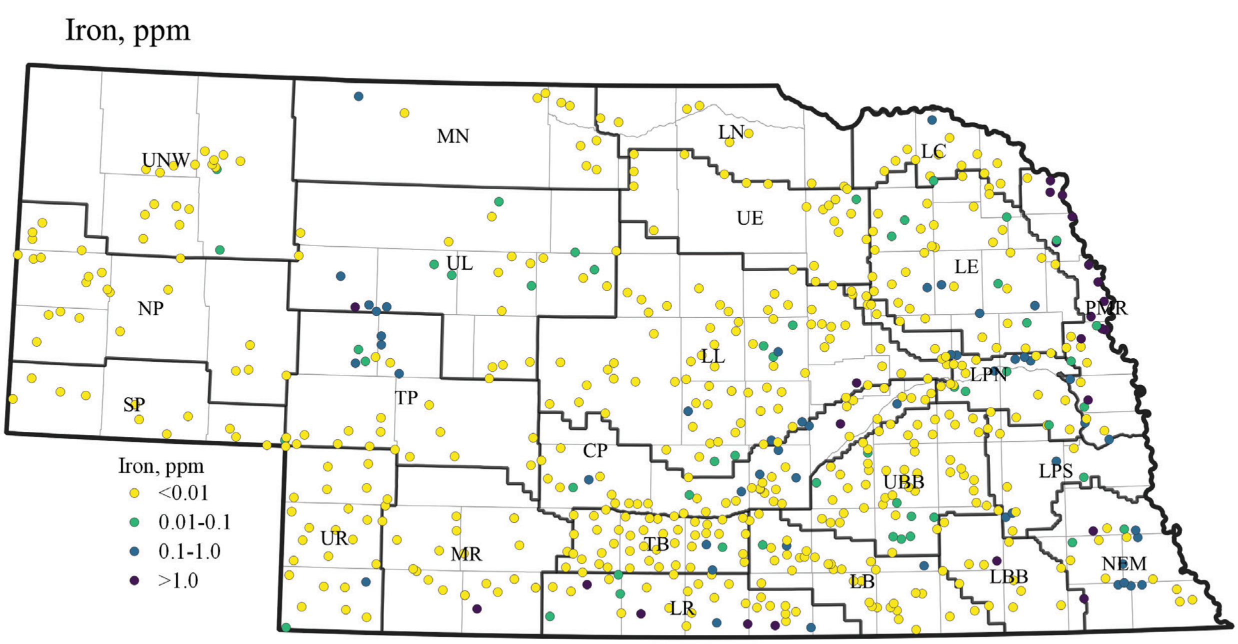

Fig. 20. Iron, ppm

12. Manganese (Mn)

The concentrations of Fe and Mn is positively correlated. The Mn level is below the reliable detection level (0.01 ppm) for 50% of the sampled wells. Ten wells supply >2.0 lb Mn per 10 ac-in. About 16% of the wells, and most wells in PMR, supply enough Mn in 10 ac-in to exceed the Mn removed in 200 bu of corn grain. As with Fe, there is a group of wells in Arthur, Grant, Hooker, and McPherson counties and wells in the Missouri River valley with relatively high Mn concentration. The mean Mn concentration is low for the Great Plains Aquifer in wells of >100 ft depth compared with elsewhere. Irrigation Mn should be considered in nutrient management planning for Paleovalley Aquifers in NEM and PMR, and for wells of <100 ft depth.

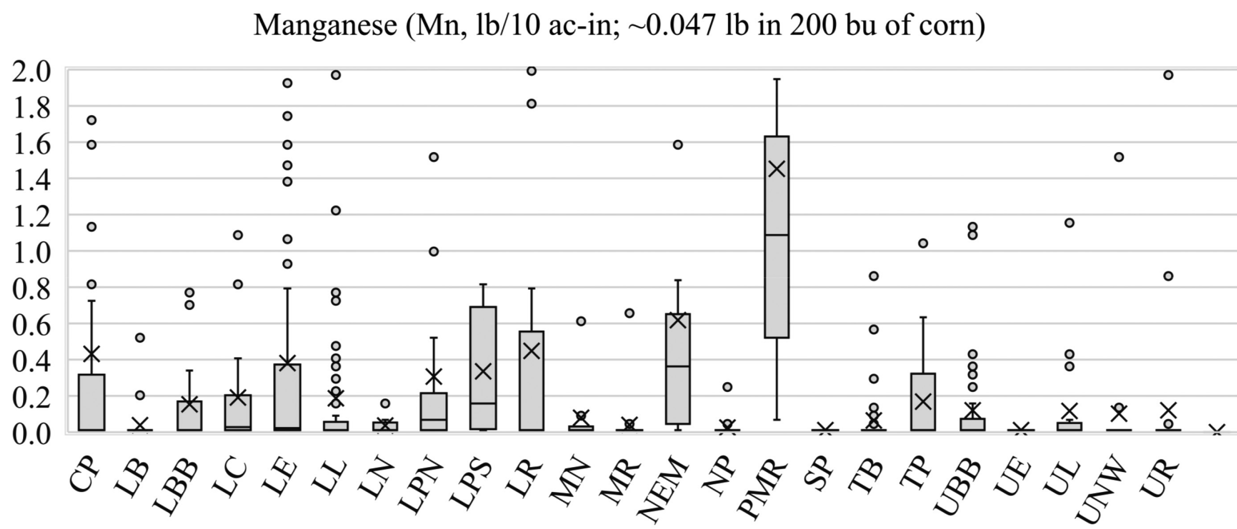

Fig. 21. Manganese (Mn, lb/10 ac-in; ~0.047 lb in 200 bu of corn)

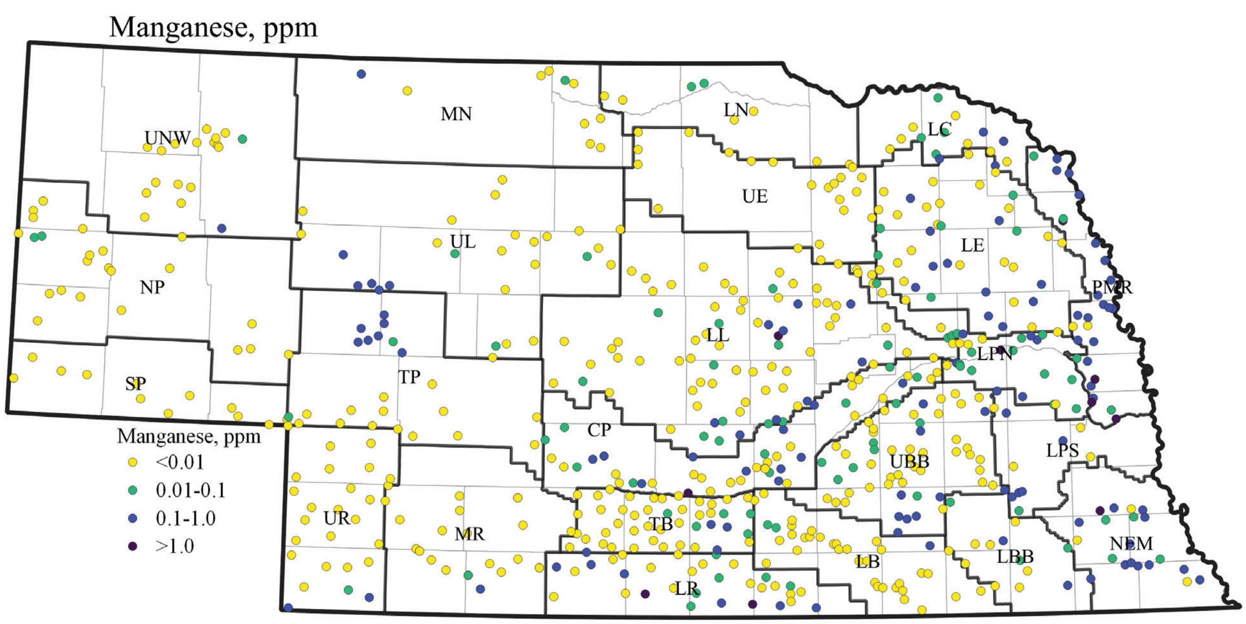

Fig. 22. Manganese, ppm

13. Copper (Cu)

The Cu level is below the reliable detection level (0.01 ppm) for 80% of the sampled wells but 6.2% supply enough Cu in 10 ac-in to exceed the Cu typically removed in 200 bu of corn grain. Fourteen wells supply >0.05 lb Cu per 10 ac-in. Irrigation is more likely to replace Cu removed in grain harvest in LPN, LPS, MR, TB, UE, and UNW than in other NRD. However, even these NRD with high means had median values of <0.01 ppm.

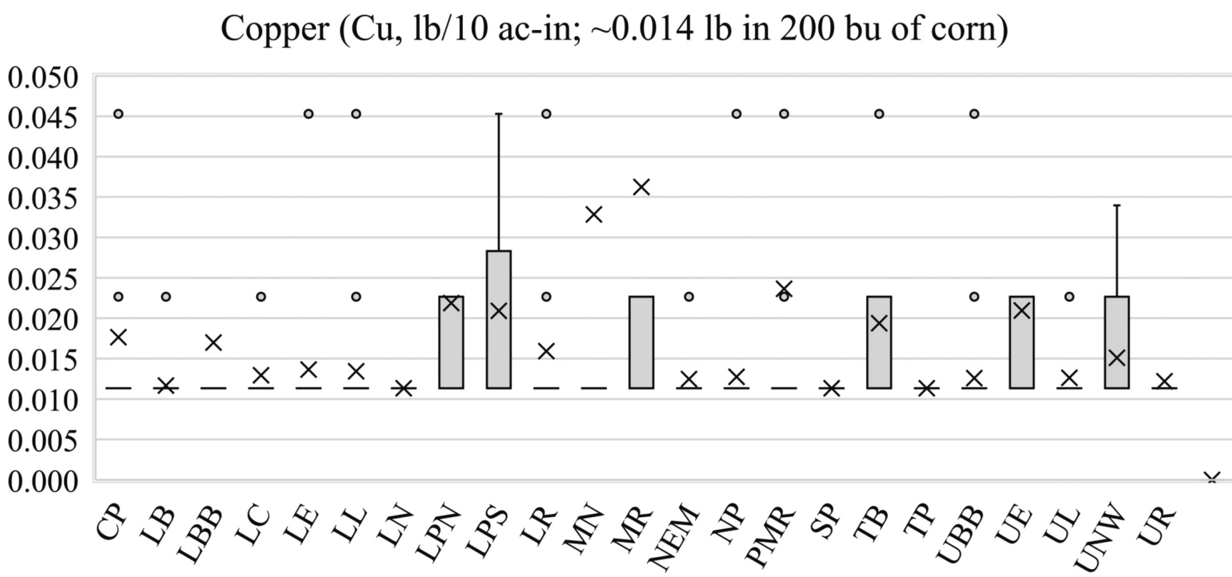

Fig. 23. Copper (Cu, lb/10 ac-in; ~0.014 lb in 200 bu of corn)

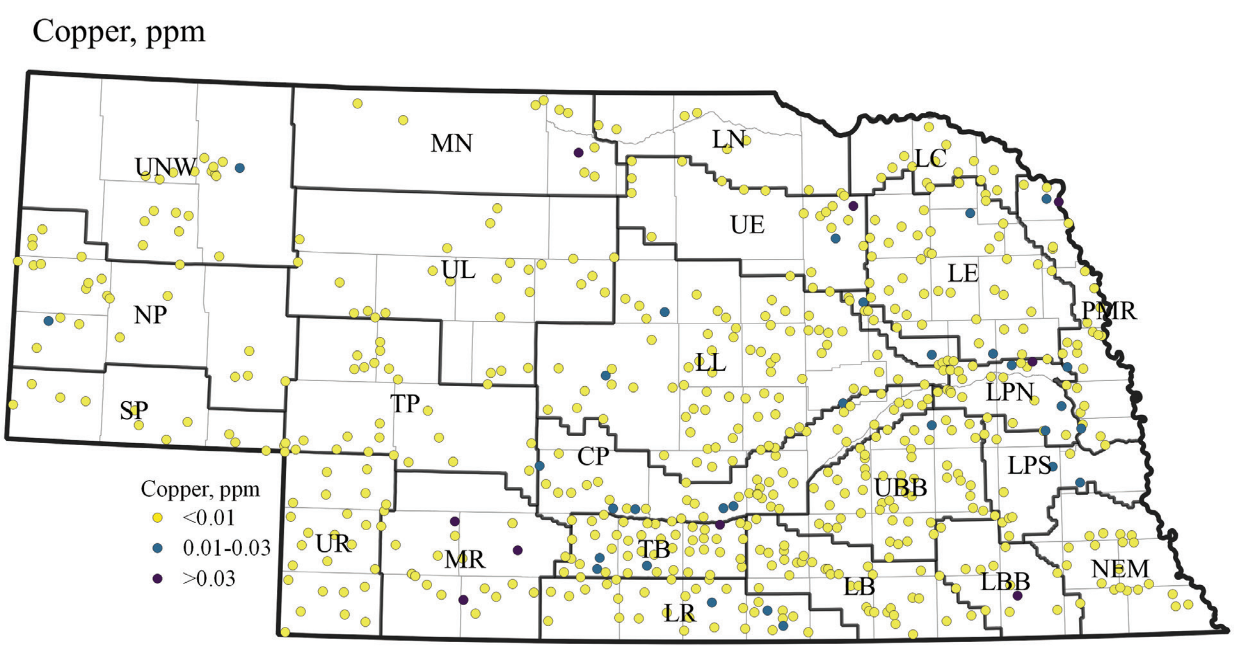

Fig. 24. Copper, ppm

14. Molybdenum (Mo)

The Mo concentration is below the reliable detection level (0.001 ppm) in 53% of the sampled wells but 16% supply enough in 10 ac-in to exceed the amount of Mo typically removed in 200 bu of corn grain. There are 10 wells that supply >0.06 lb Mo per 10 ac-in. Irrigation water concentrations are relatively low in LB, LN, NEM, SP, UE, and UL and relatively high in UR compared with other NRD.

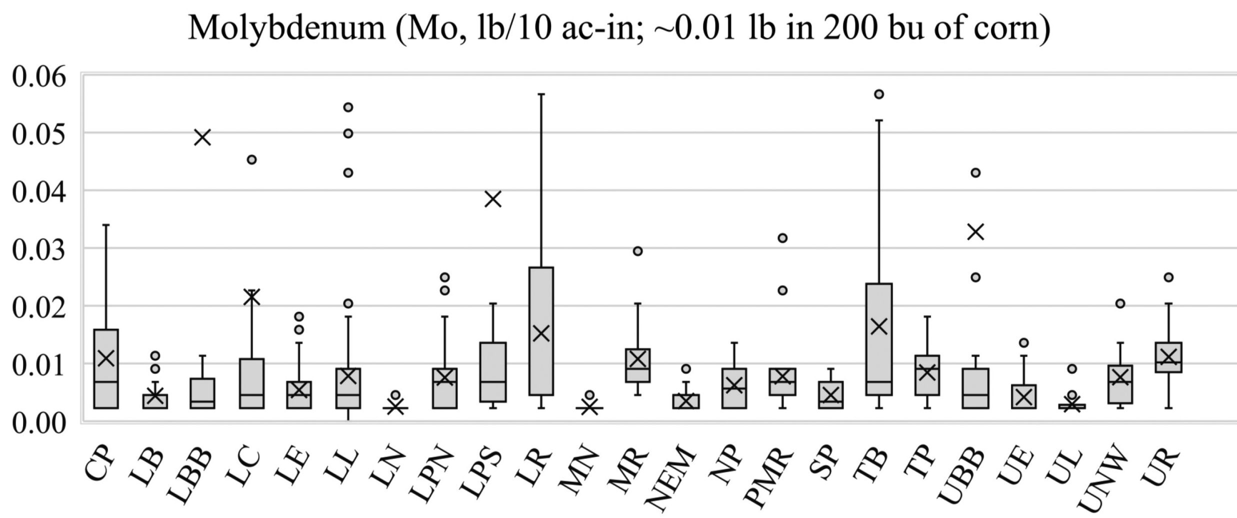

Fig. 25. Molybdenum (Mo, lb/10 ac-in; ~0.01 lb in 200 bu of corn)

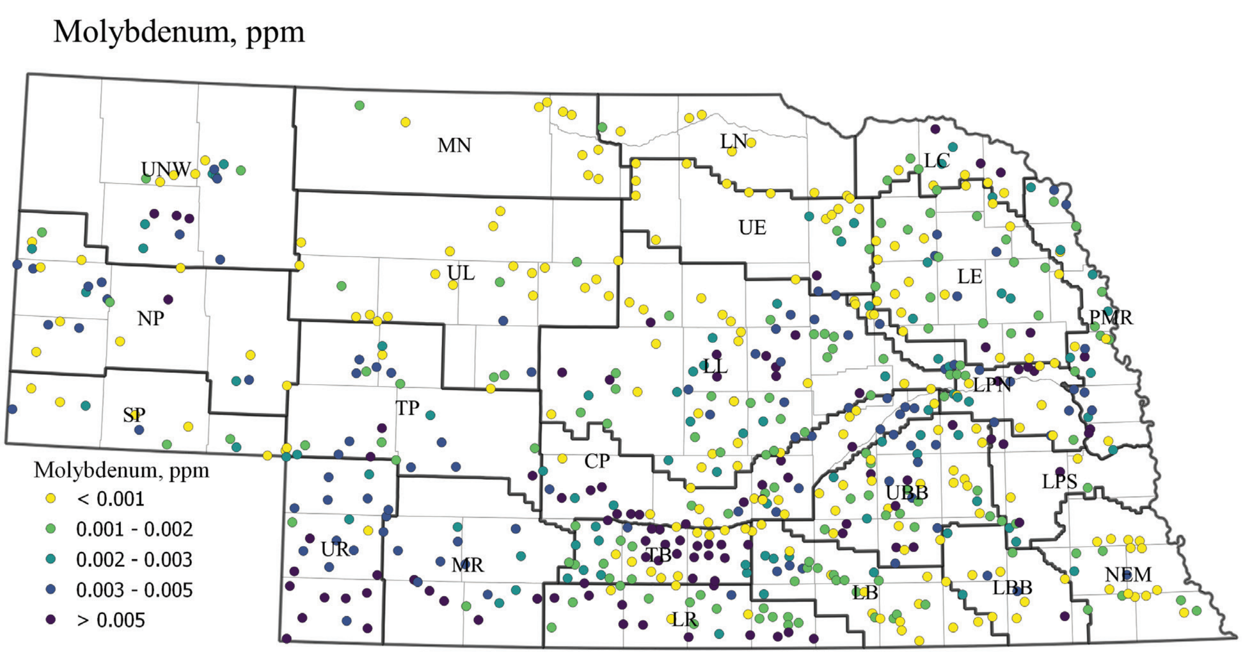

Fig. 26. Molybdenum, ppm

15. Boron (B)

The B levels are above the reliable detection level (0.01 ppm) for 96.5% of the sampled wells but only 4.4% supply enough B in 10 ac-in to exceed the B typically removed in 200 bu of corn grain. Three wells supply >0.8 lb B/10 ac-in. Irrigation is more likely to replace B removed in grain harvest in NEM, PMR, and SP than in other NRD. The average B concentration was relatively high for the Paleovalley Aquifers compared with other aquifers. No wells have a toxic level (>1 ppm) of B.

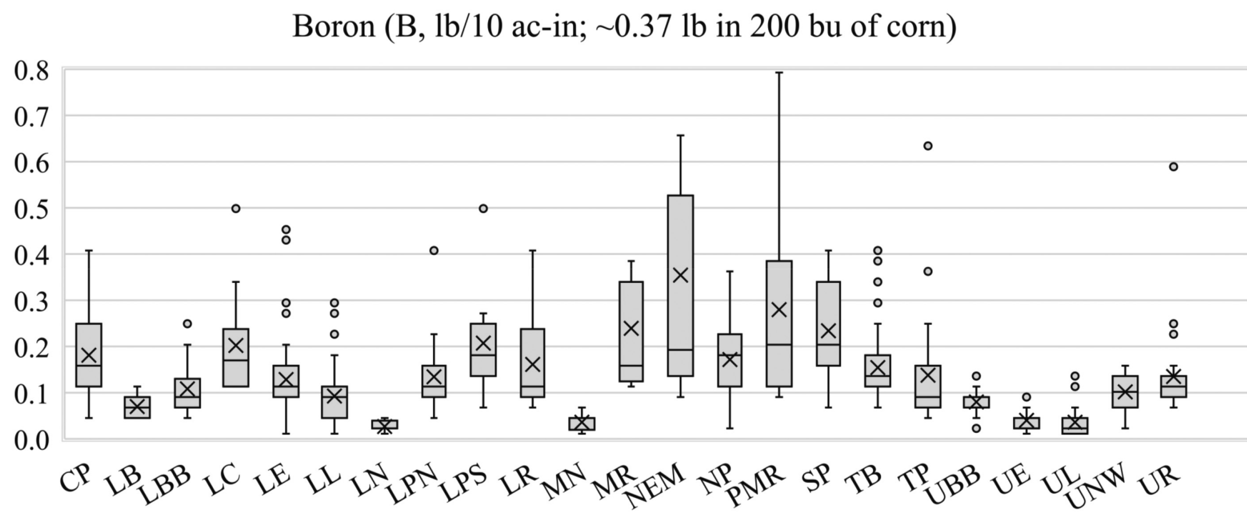

Fig. 27. Boron (B, lb/10 ac-in; ~0.37 lb in 200 bu of corn)

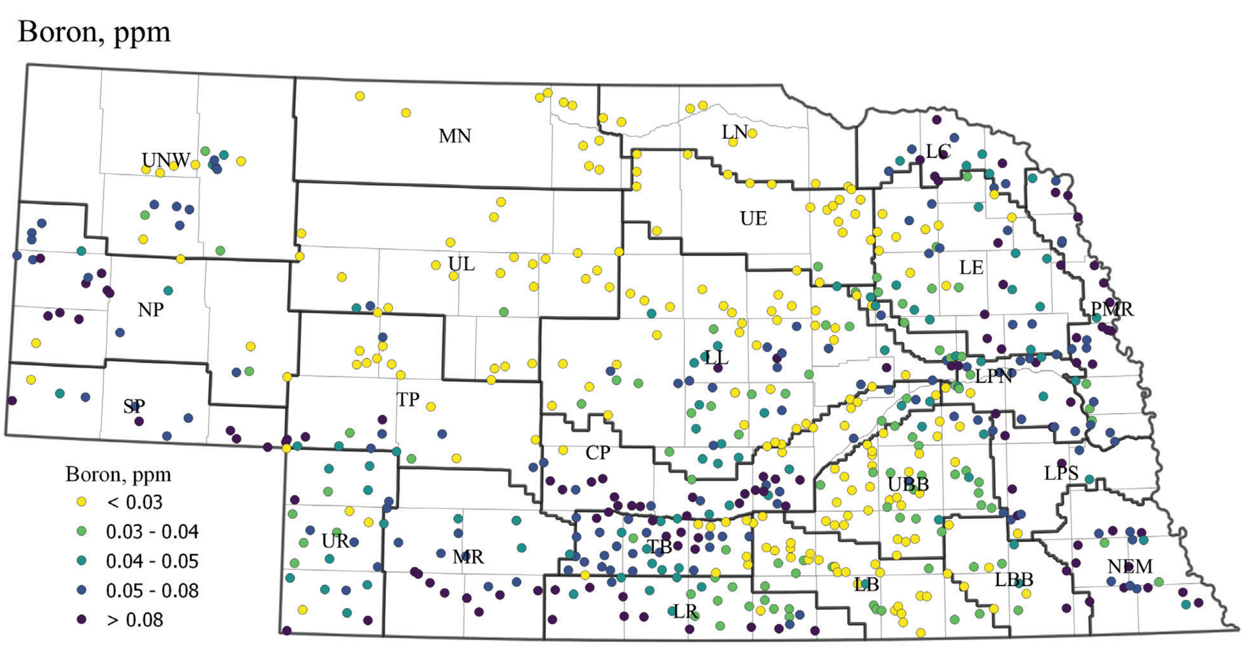

Fig. 28. Boron, ppm

16. Chloride (Cl)

Irrigation can supply much Cl with >50 lb/10 ac-in typically applied in CP, LR, SP, and TB. The Cl supply is generally much less in some NRD and in the Sandhills. Three wells supply >250 lb Cl/10 ac-in. Grain harvest removes very little Cl and all wells supply enough Cl for a positive balance. Kansas State University recommends the application of 10–20 lb Cl/ac when soil tests indicate a need for Cl application (Diaz, 2019). The Cl applied in 10 ac-in exceeds 10 lb/ac with 63% of the sampled wells. The mean Cl concentration was relatively high for wells of <100 ft depth in the High Plains Aquifer compared with other aquifer categories.

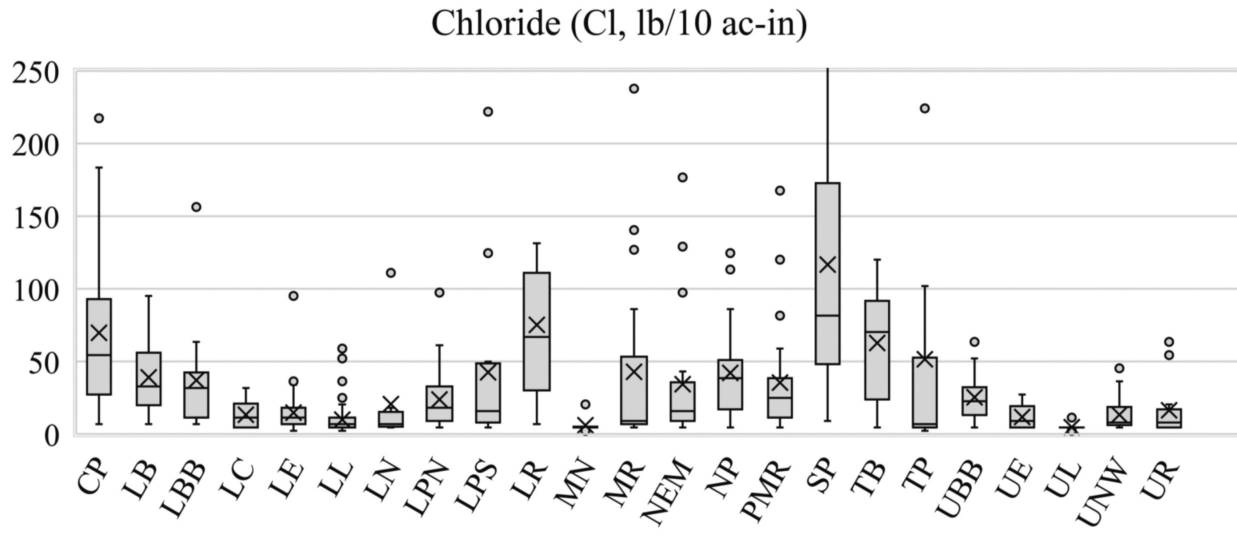

Fig. 29. Chloride (Cl, lb/10 ac-in)

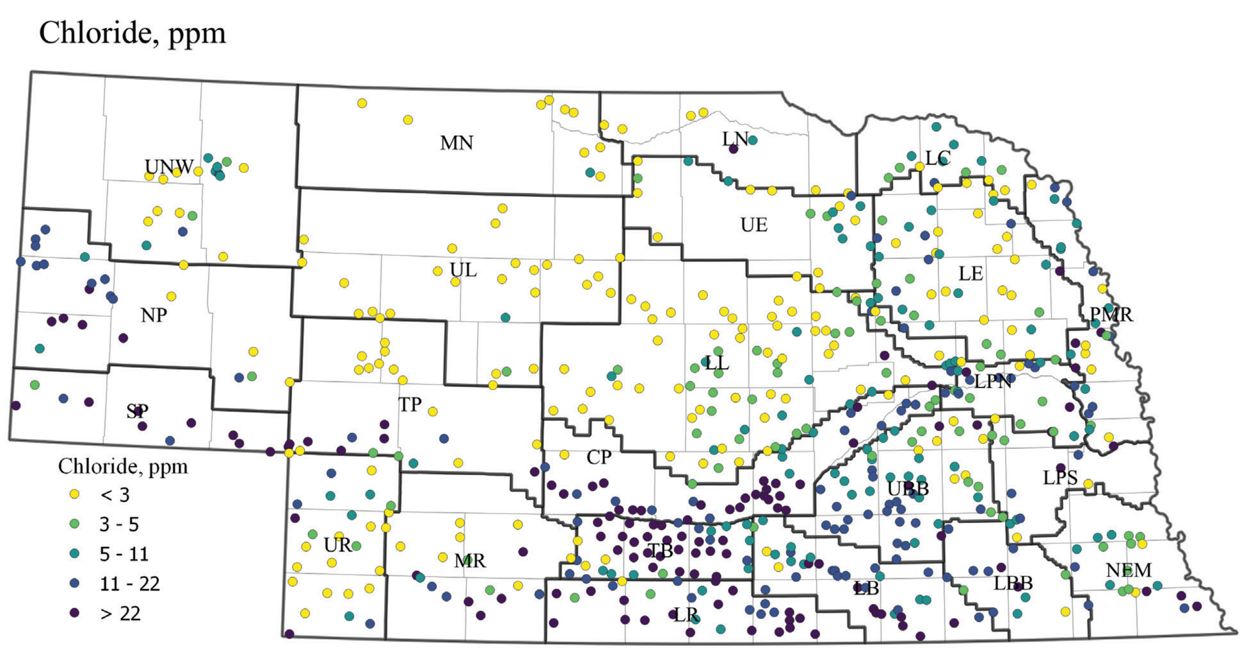

Fig. 30. Chloride, ppm

17. Sodium (Na) and Adjusted Sodium Adsorption Ratio (SARadj)

Sodium is not an essential nutrient for crop growth but contributes to SAR and SARad so that the Na concentration is highly correlated with SAR_{adj} (r = 0.94). High SAR results in reduced soil aggregation and water infiltration, hard dry soil, and slick wet soil. Six wells supply >400 lb Na/10 ac-in. Two wells have outlying values of SAR_{adj} >5.5. The Na applied and SAR are relatively low for the Sandhills, and LC, LE, LL, LN, MN, UE, and UL compared with other NRD but generally relatively high for wells of <100 ft depth in the Great Plains Aquifer, CP and NP. The effect of high SAR on soil properties decreases with increased EC (Hoffman et al. 2010). An irrigation SAR of 10 can eventually degrade soil to severely reduce water infiltration if the EC <0.5 dS/m but the effect is only moderate if EC is >1.0 dS/m. Therefore, irrigation from the wells with relatively high SAR in this study is not likely to affect soil aggregate stability and water infiltration as all wells with SAR_{adj} >4.0 had EC >1.0. Some NRD, however, likely have wells of high SAR_{adj} that were not developed for irrigation and were not sampled for this study. Therefore, the results of this survey of active irrigation wells are not applicable to all groundwater sources but surveyed wells with high SAR_{adj} indicate the potential for excessive SAR_{adj} with neighboring wells.

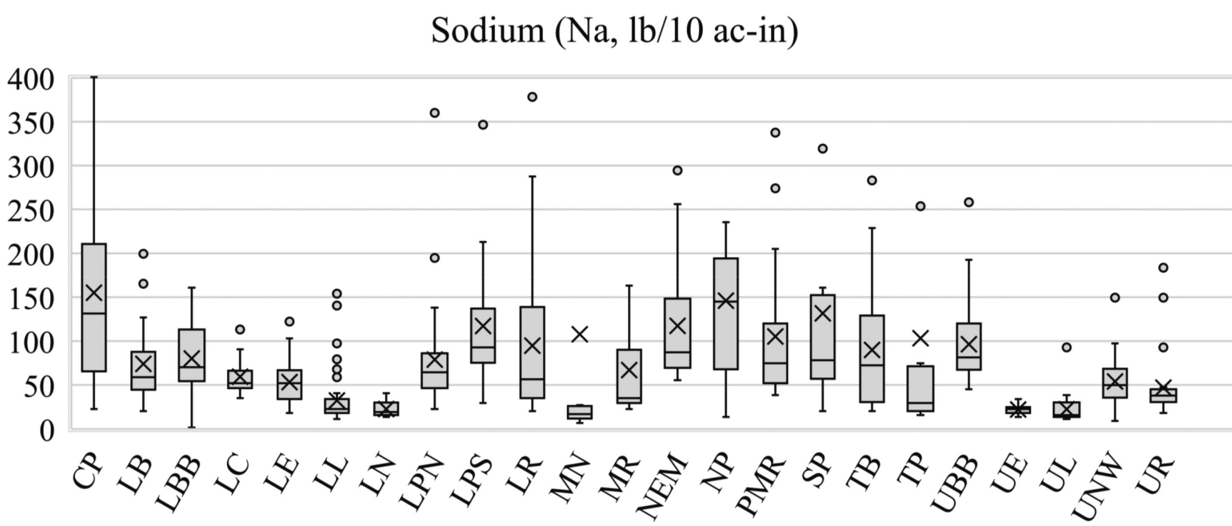

Fig. 31. Sodium (Na, lb/10 ac-in)

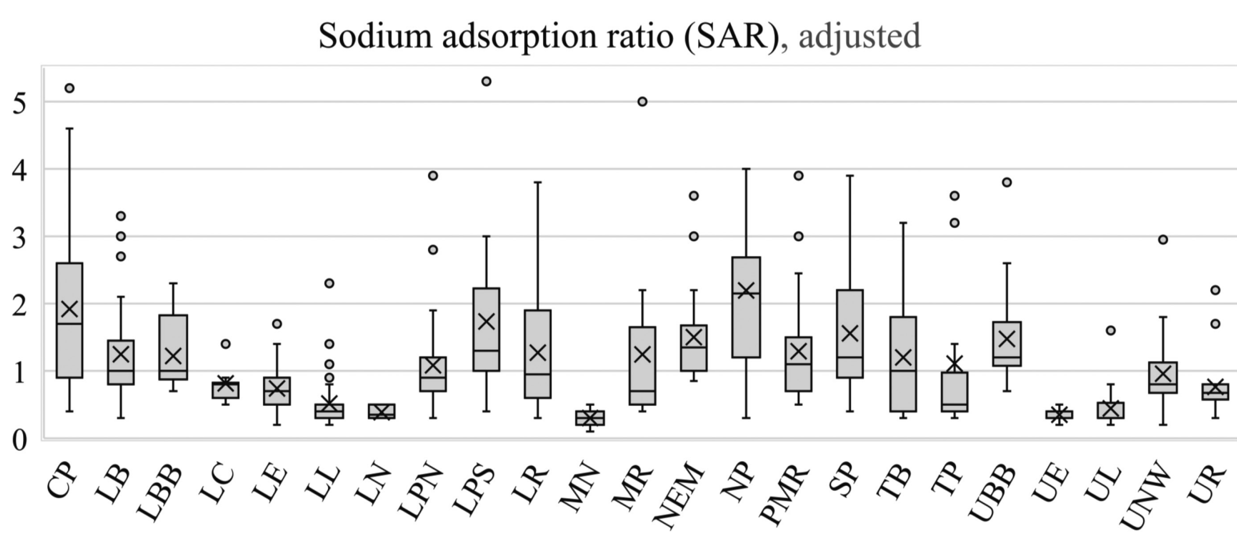

Fig. 32. Sodium adsorption ration (SAR), adjusted

Sodium, ppm

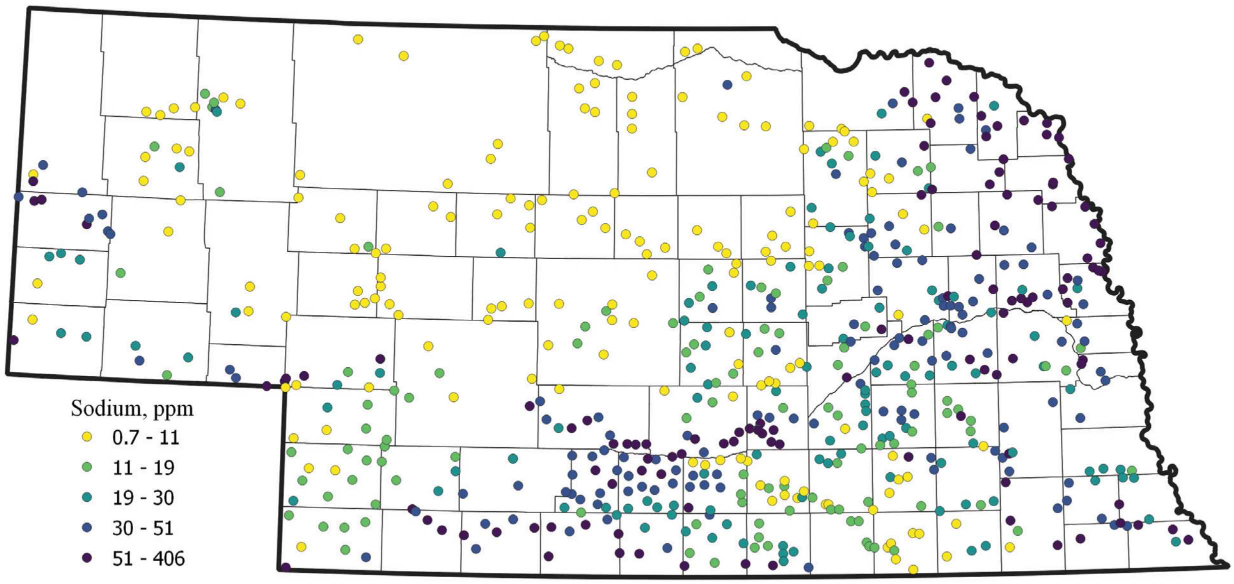

Fig. 33. Sodium, ppm

Sodium adsorption ratio, adjusted (SAR)

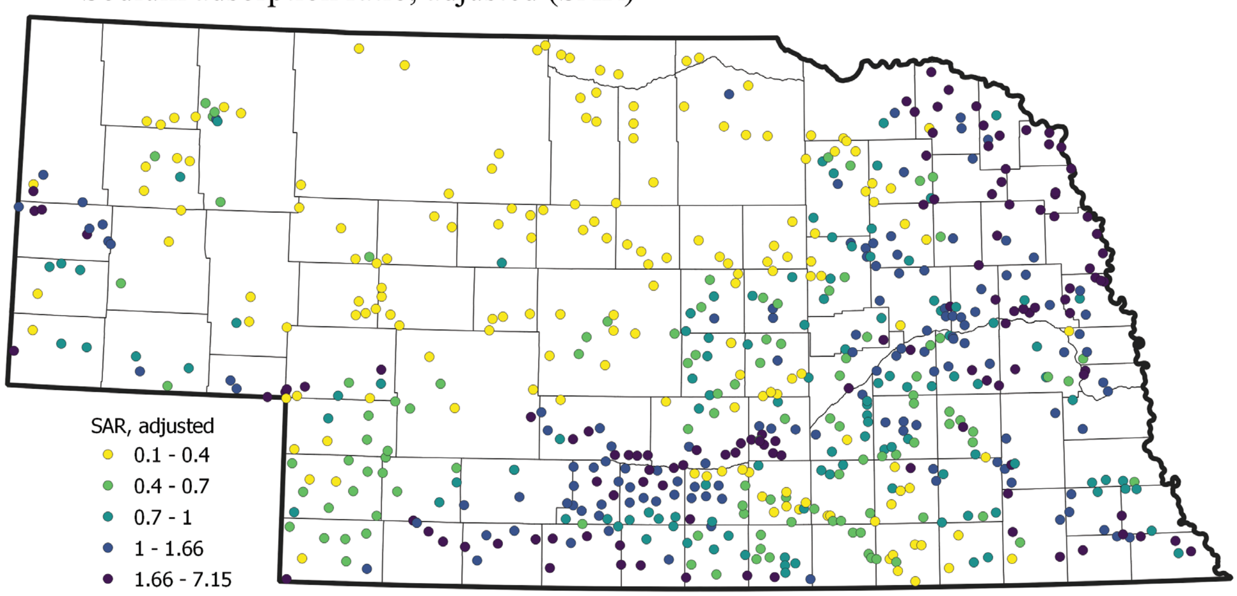

Fig. 34. Sodium adsorption ratio (SAR), adjusted

18. Water pH

There is only one well with pH >8.3 and two with pH <6.9. The pH is relatively high for sample wells in MR and low for LPN and LPS compared with other NRD. Water pH is lower in eastern compared with western Nebraska.

19. Electrical Conductivity and Total Dissolved Solids

Total dissolved solids and salinity are indicated by EC. Salts applied in irrigation water affect soil EC. The TDS concentration is highly correlated with P (r = 0.62), K (r = 0.50), Ca (r = 0.93), Mg (r = 0.87), S (r = 0.87), Cl (r = 0.72), and HCO_3 (r = 0.62), but TDS is less correlated with the micro-nutrient concentrations and pH. Corn and dry bean are relatively sensitive to TDS in soil solution but soybean, sugar beet and wheat are relatively tolerant. Annual precipitation and the annual average amount of water that percolates beyond the root zone affect the interpretation of water EC (Hoffman et al., 2010). For example, irrigation with water of EC >3 dS/m can be expected to eventually reduce corn and dry bean yield in western Nebraska but not in eastern Nebraska. The TDS was calculated from EC and so the images are alike except for different units of measurement (r = 0.997). There are four wells with EC >2.5 dS/m, two of which are in TP with the potential to eventually raise soil EC enough to reduce corn and dry bean yield. The EC and TDS are relatively high for wells of <100 ft in the Great Plains Aquifer and for CP and TB and relatively low in the Sandhills and for LN, MN, TP, UL, and UR. Some NRD, however, likely have borer holes of high EC that were not developed for irrigation and were not sampled for this study. Therefore, the results of this survey should not imply a lack of risk of excessive EC but surveyed wells with high EC indicate the potential for excessive EC with neighboring wells.

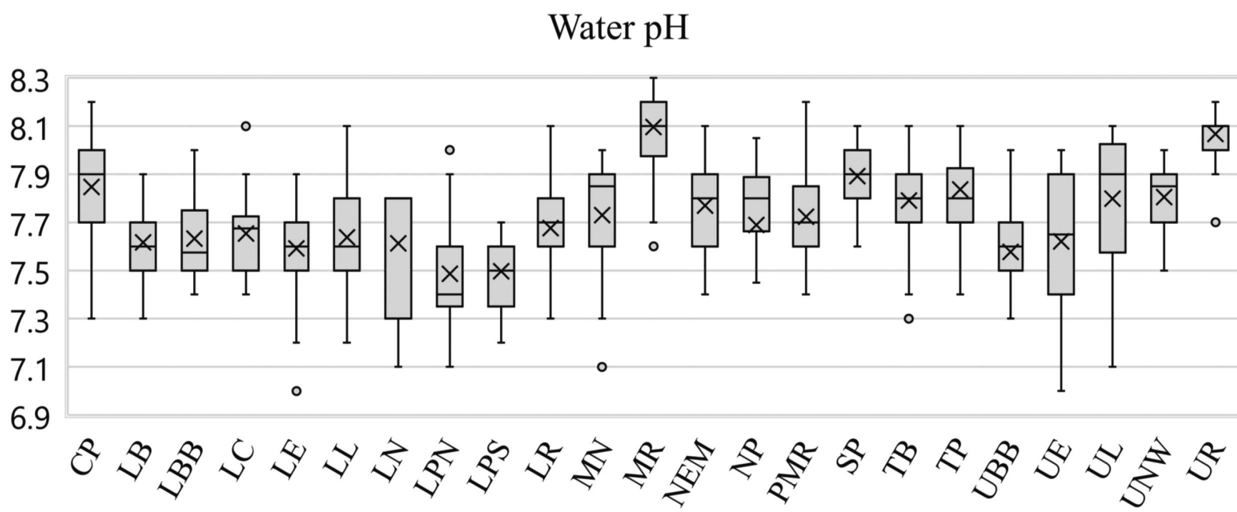

Fig. 35. Water pH

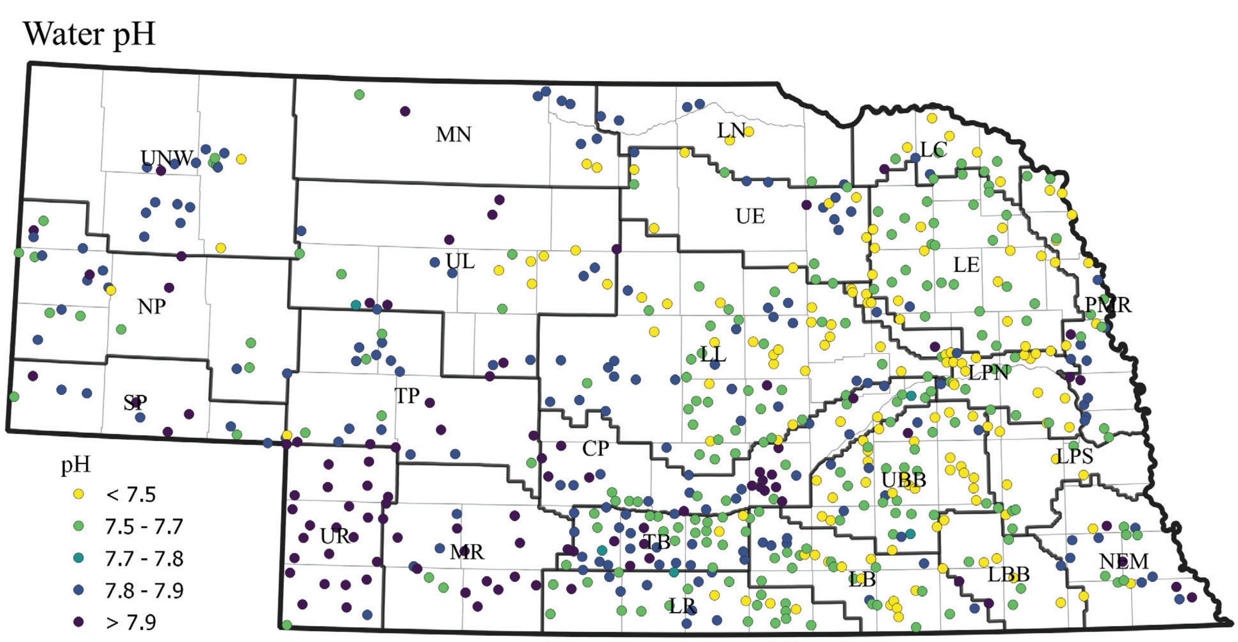

Fig. 36. Water pH

20. Total Hardness

Total hardness is correlated with EC and TDS (r = 0.95) as all are affected by the Ca plus Mg concentration. Total hardness is >2000 lb/10 ac-in for eight wells. Hardness is low in the Sandhills, LN, MN, and UL but relatively high for the High Plains Aquifer wells of <100 ft depth, and in CP, PMR and TP compared with other NRD.

21. Bicarbonate, Agricultural Lime Equivalent and Alkalinity

Lime in irrigation water is valuable for preventing soil acidification but $CaCO_3$ can accumulate to plug nozzles and drip-irrigation emitters and it reacts with P and some micronutrients applied through fertigation. The agricultural lime equivalent is calculated from the HCO_3 content as there is very little CO_3 in the water. Nearly all sampled wells supply >50 lb/ac-in of agricultural lime (60% effective Ca CO_3 equivalent) with an average application of 1014 lb of agricultural lime in 10 ac-in. About 340 lb of agricultural lime is needed to neutralize the acidification effect of 200 lb of fertilizer-N; 70% of the sampled wells supply at least 340 lb of agricultural lime equivalent in 10 ac-in. Lime supply is relatively less for the Sandhills and LN, MN, UE, and UL compared with other NRD. About 18% of the sampled wells in the Sandhills supply enough liming effect in 10 ac-in to neutralized the acidification resulting from application of 200 lb/ac of fertilizer N but 39% supply enough liming effect with 15 ac-in. Exchangeable

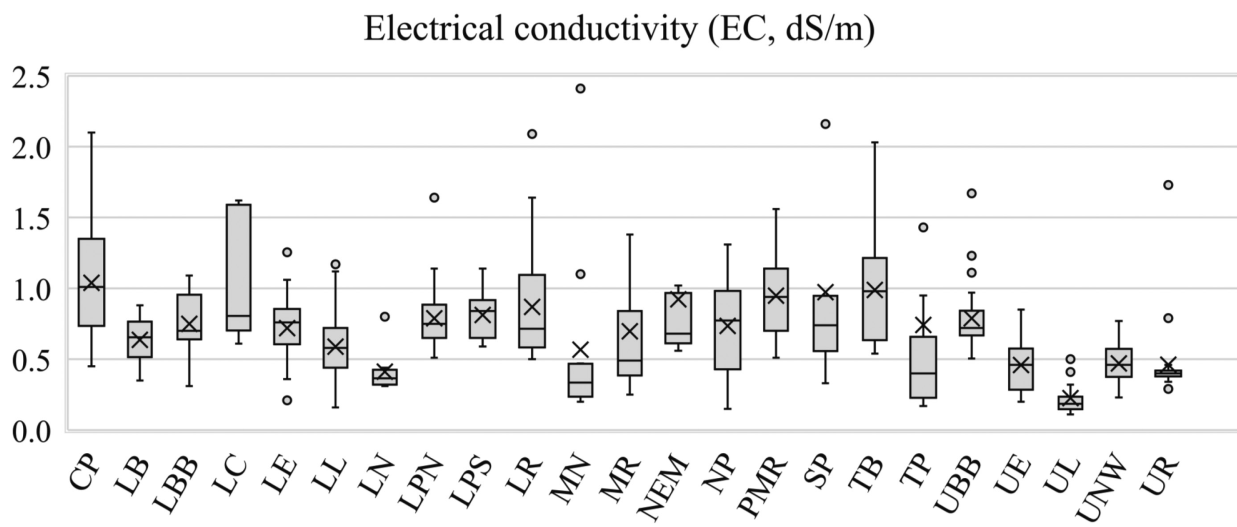

Fig. 37. Electrical conductivity (EC, dS/m)

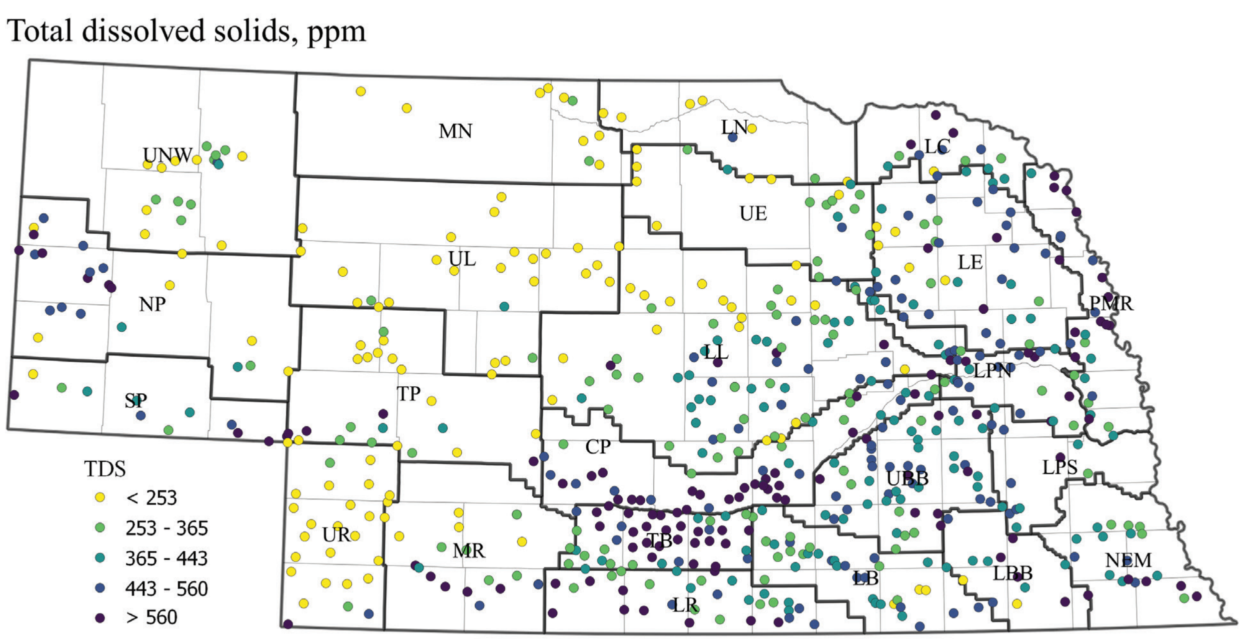

Fig. 38. Total dissolved solids, ppm

aluminum in surface soil and sub-soil of pH <5 can reduce yields but Ca supplied from irrigation is generally adequate to displace the aluminum and cause it to leach so that exchangeable aluminum does not build up to toxic levels.

Total alkalinity is calculated from the $CaCO_3$ (ppm) equivalent which is calculated from HCO_3 (ppm). Total alkalinity is very closely related to HCO_3 and equal to 0.8239 x HCO_3 ($R^2 = 1.0$).

22. Correlation Between Water Properties

Correlations indicate associations but not causal effects of properties. Correlation coefficients of <0.10 are not considered to be statistically significant. There are strong positive correlations between K, Ca, Mg, S, B, Cl, Na, SARad, TDS, and EC (see following table; ns indicates no significant correlation). Water pH, Zn, Fe, Cu, Mn, and Mo vary independently of other water properties except for a relationship

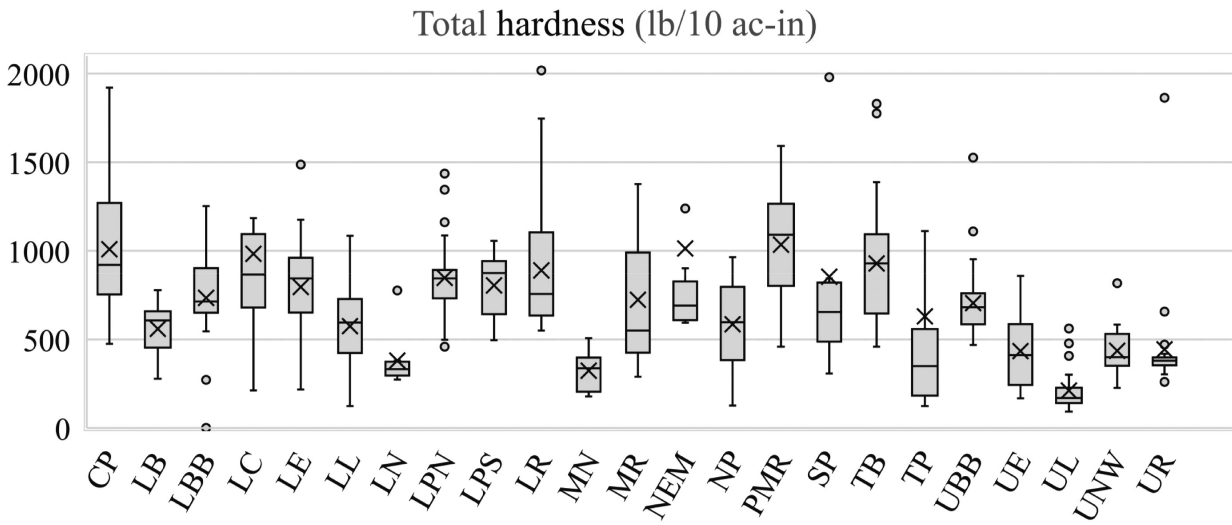

Fig. 39. Total hardness (lb/10 ac-in)

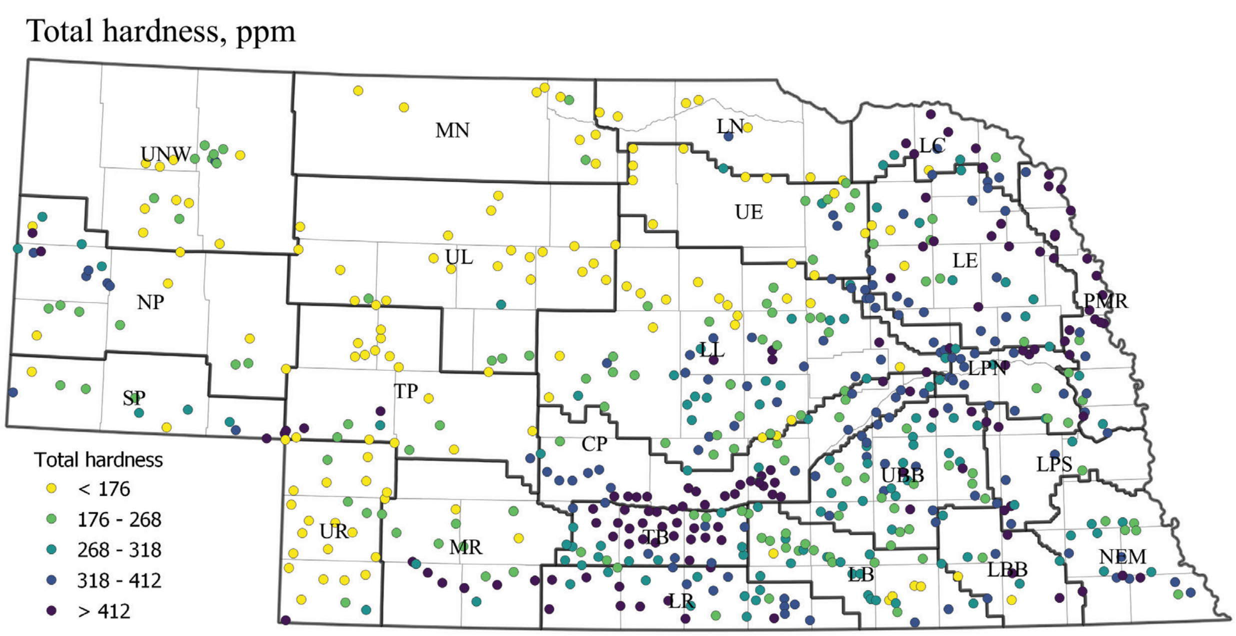

Fig. 40. Total hardness, ppm

of Fe with Mn. Correlation of well-depth with most water properties is stronger for the Great Plains Aquifer outside the Sandhills (coefficients in parentheses) than for the rest of Nebraska (coefficients with no parentheses). Most water properties tend to have decreasing values with greater well depth.

Conclusions

Nutrients applied in irrigation water can be important to nutrient management. The amount of Ca, Mg, S, and CI applied in 10 ac-in of water exceeds that removed in the harvest of 200 bu of corn grain for the majority of sampled wells. Substantial amounts of K, Mn and Mo are applied in >15% of the sampled wells. The agricultural lime equivalent applied in 10 ac-in is enough to neutralize the acidifying effect of 200 lb of fertilizer-N for 70% of the wells. The sampled wells supplied high-quality water for irrigation except for 0.3% of the wells with high salinity that could eventually reduce the yield of salt-sensitive crops such as corn and dry bean. The SAR is not expected to be harmful to soil properties as the high SAR wells also have >1 dS/m EC.

Water properties vary between and within NRD and aquifer categories. The differences between NRD account for

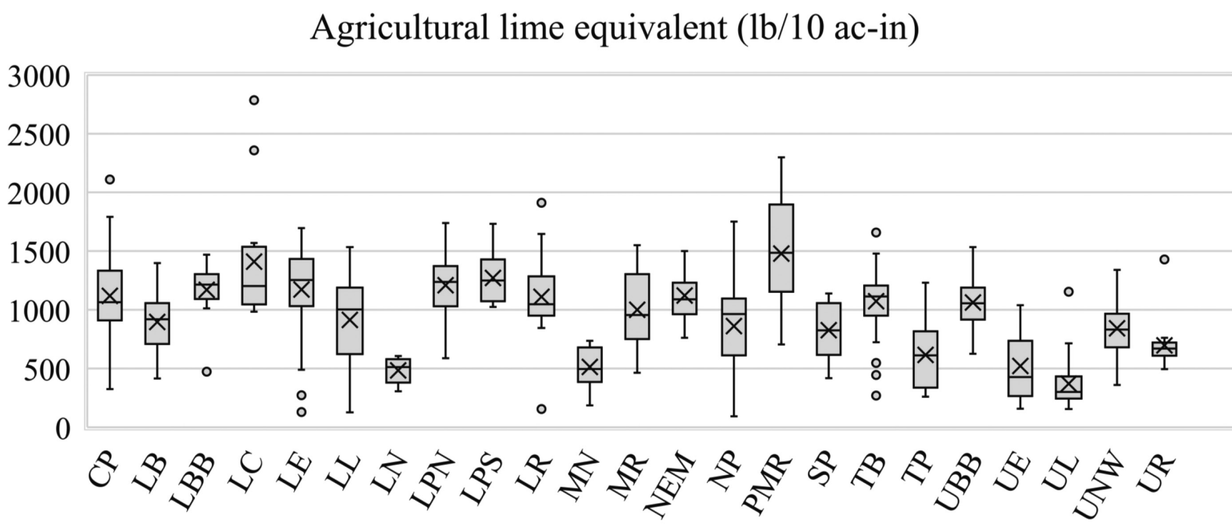

Fig. 41. Agricultural lime equivalent (lb/10 ac-in)

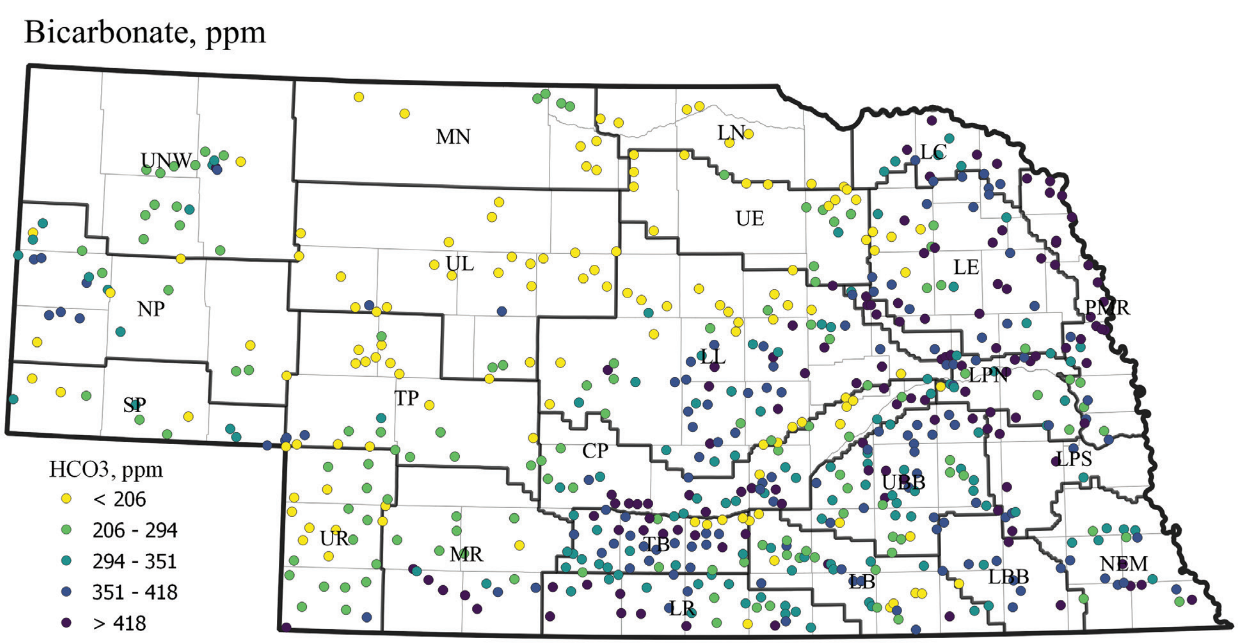

Fig. 42. Bicarbonate, ppm

Table 2.

Property	Well-depth	NO_3	P	K	Ca	Mg	S	Zn	Fe	Mn
NO_3	-0.18 (-0.23)									
P	ns (-0.19)	0.14								
K	ns (-0.21)	0.11	ns							
Ca	-0.31 (-0.34)	0.23	ns	0.37						
Mg	-0.28 (-0.34)	0.12	ns	0.43	0.85					
S	ns (-0.34)	ns	ns	0.41	0.83	0.86				
Zn	ns (ns)	ns	ns	0.02	ns	ns	ns			
Fe	-0.20 (-0.18)	-0.17	ns	0.07	0.18	0.30	0.15	ns		
Mn	-0.30 (-0.13)	-0.23	0.20	0.23	0.16	0.22	0.15	ns	0.40	
Cu	ns (ns)	0.13	ns	0.10	ns	ns	ns	0.22	0.12	ns
Mo	ns (ns)	ns	ns	ns	0.10	0.07	0.07	ns	ns	ns
B	ns (-0.24)	ns	-0.13	0.39	0.64	0.80	0.74	ns	0.27	0.19
Cl	-0.17 (-0.38)	0.27	ns	0.48	0.59	0.56	0.63	ns	ns	0.11
Na	-0.22 (-0.39)	0.15	ns	0.44	0.64	0.69	0.77	ns	0.10	0.16
SARad	-0.22 (-0.40)	0.13	ns	0.41	0.49	0.51	0.59	ns	0.07	0.15
pH	0.22 (0.20)	-0.21	-0.24	0.14	-0.11	-0.04	-0.06	ns	ns	ns
TDS	-0.32 (-0.39)	0.27	ns	0.51	0.93	0.88	0.88	ns	0.16	0.17
EC	-0.33 (-0.39)	0.26	ns	0.51	0.93	0.87	0.88	ns	0.16	0.17
Hardness	-0.31 (-0.35)	0.20	ns	0.42	0.98	0.93	0.87	ns	0.23	0.18
HCO_3	-0.48 (-0.18)	ns	ns	0.22	0.65	0.57	0.31	ns	0.28	0.24

Table 3.

Property	Cu	Mo	B	Cl	Na	SARad	pH	TDS	EC	Hardness
Mo	ns									
B	ns	ns								
Cl	ns	ns	0.50							
Na	ns	ns	0.65	0.76						
SARad	ns	ns	0.57	0.67	0.94					
pH	ns	ns	0.08	ns	ns	ns				
TDS	ns	0.10	0.71	0.74	0.84	0.71	ns			
EC	ns	0.10	0.71	0.75	0.84	0.71	ns	1.00		
Hardness	ns	0.10	0.71	0.60	0.68	0.52	ns	0.95	0.95	
HCO_3	ns	0.10	0.47	0.27	0.45	0.45	ns	0.61	0.61	0.65

an average of 24% of the variation in water properties ranging from <10% of the variation in Zn, Fe, Mn, Cu, and Mo to 38% of the variation in HCO_3. Aquifer categories account for an average of just 12% of the variation in water properties with much of this due to results for sampled wells in the Sandhills compared with wells of <100 ft depth in the High Plains Aquifer. Because most variation in water properties is not accounted for by the NRD and aquifer categories, water from each individual or grouping of near-by wells should be tested to fully optimize nutrient management.

ACKNOWLEDGEMENTS

This survey of the properties of water from irrigation wells was a success during the COVID-19 pandemic due to the participation of many collaborators. The role of the managers and water resource specialists and technicians from the Nebraska's 23 Natural Resources Districts in collecting, preserving and submitting the water samples was essential to success. The Ward Laboratories team provided advice and analyzed the water samples with their typical promptness and high-quality control. Water specialists from the Nebraska

Department of Environment and Energy advised on the protocol and the Department provided funding to assist with the cost of sample analysis. The Nebraska Department of Natural Resources assisted in adding well data to the dataset and was the source of a center-pivot distribution map. Katie Pekarek, UNL Extension educator for water quality, and Dustin Wilcox, Nebraska Association of Resources Districts, facilitated communication logistics.

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APPENDIX I: MATERIALS AND METHODS

Water samples were collected from irrigation wells in all 93 counties across Nebraska during June to September of 2020 by staff of the 23 NRD staff (https://www.nrdnet.org/). The number of wells sampled varied from four to >12 per county depending on the extent of irrigation in each county. The sampled wells were at least three miles apart. Clean and ready-to-use sample bottles were provided by Ward Laboratories Inc. in Kearney NE (www.wardlab.com). The sample volume was >300 ml. The wells were pumped for at least 15 minutes before sample collection. The samples were refrigerated and sent to Ward Laboratories for analysis within 10 days of collection.

Irrigation water was sampled from 642 wells across the 23 NRD including 43 for Central Platte (CP), 34 for Little Blue (LB), 14 for Lower Big Blue (LBB), 14 for Lewis and Clark (LC), 49 for Lower Elkhorn (LE), 81 for Lower Loup (LL), 8 for Lower Niobrara (LN), 29 for Lower Platte North (LPN), 13 for Lower Platte South (LPS), 32 for Lower Republican (LR), 10 for Middle Niobrara (MN), 25 for Middle Republican (MR), 20 for Nemaha (NEM), 24 for North Platte (NP), 23 for Papio-Missouri River (PMR), 12 for South Platte (SP), 45 for Tri-Basin (TB), 22 for Twin Platte (TP), 54 for Upper Big Blue (UBB), 20 for Upper Elkhorn (UE), 26 for Upper Loup (UL), 18 for Upper Niobrara White (UNW), and 26 for Upper Republican (UR). Duplicate samples for quality verification of laboratory procedures were submitted for 59 wells. The sampled wells were geo-referenced with WGS-84 latitude and longitude to three or more decimal places. Each NRD maintained a sample log with sample ID code, NRD, county, G-number (registration number) for the well, latitude, longitude, date of sampling, time of sampling, and other information to which the sample analysis results were later added.

The samples were analyzed by Ward Laboratories Inc. using methods approved by the U.S. Environmental Protection Agency (EPA) to ensure compliance with regulations. These included:

pH (EPA, 1982);

EC (EPA, 1995) with TDS equal to EC multiplied by 600 or by 640 if EC was >5 dS/m or mmho/cm;

HCO_3 with 0.25 N HCl titration to pH 4.4 (EPA, 1978; APHA, 2012);

NO_3-N with cadium reduction (Kenney and Nelson, 1982; EPA, 1993; Bridgewater, 2012);

NH_4-N with the salicylate method (Kenney and Nelson, 1982; EPA, 2017);

total P with ICAP analysis (Hosomi and Sudo, 1986);

Cl with the mercury(II) thiocyanate method (EPA, 1971; Gelderman et al., 1998; and

K, Ca, Mg, Na, S, Cu, Fe, Mn, Mo, and Zn concentrations using inductively coupled plasma—optical emission spectrometry (ICP-OES) (Martin, 2003; Gottler, 2012);

SAR (Martin, 2003);

Adjusted SAR was calculated by replacing Ca with a Ca equilibrium value in the SAR equation with Ca equilibrium being a function of Ca divided by 2 x HCO_3 (Lesch and Suarez, 2009). The Ca equilibrium concentration was commonly less than the Ca concentration resulting in SAR_{adj} typically being greater than SAR.

Some properties were calculated after conversion of concentrations from ppm to meq/L with ppm divided by mg/meq, that is, dividing ppm of Ca by 20, Mg by 12, and HCO_3 by 61.

The liming effect was calculated by multiplying the concentration of HCO_3 (ppm) by 50 (mg/meq $CaCO_3$), dividing by 61 (mg/meq of HCO_3), and multiplying by 0.2265 to get 100% effective $CaCO_3$ applied (lb/ac-in). The results were reported as lb/10 ac-in of irrigation water with 60% effective $CaCO_3$ equivalent (ECCE) agricultural lime by dividing 100% effective $CaCO_3$ by 0.6 and multiplying by 10 ac-in.

Total hardness was calculated as meq/L of Ca plus Mg multiplied by 50 (mg/meq $CaCO_3$) to get ppm of $CaCO_3$ hardness. Total alkalinity (meq/L) was calculated by multiplying the total equivalent of HCO_3 plus CO_3 by 50. Data for well depth and the pumping and static levels were obtained from the Nebraska Department of Natural Resources groundwater database (https://dnr.nebraska.gov/data/groundwater-data).

The data analyses were performed with Statistics 10 (Analytical Software, Tallahassee, FL , www.statistix.com/) and Microsoft Excel. Values that were below the level of reliable detection were converted to the mid-value between zero and the minimum reliable detection level. Nutrient levels were reported as pounds of nutrient element per 10 ac-in of irrigation water by multiplying the ppm value by 2.265. Average annual irrigation may range from <5 ac-in in southeast Nebraska to >15 ac-in in parts of the Sandhills or western Nebraska, but the reader can use the presented information to estimate mean annual nutrient application for a specific field or area.

The map images were created with QGIS 3.14 Pi (a free and open source Geographic Information System; https://qgis.org/en/site/) with either 20% of the wells allocated to each legend category or a logarithmic scale for properties that were mostly below the reliable measurement level.

Appendix II. Repeatability of Laboratory Results

The repeatability of lab results within submitted batches of samples was assessed with duplicate samples from 59 wells (Table 4). The ratio of the F-value for wells to the F-value for the duplicates range from 23.6 to 21,122 with a median ratio

Table 4.

Parameter	pH	SAR	EC	Na	Ca	Mg	K	Hardness	NO3	S
F-value: well	40.1	291	45.8	125	58	96	31.2	40.1	106	39.1
F-value: dupl	1.7	0.4	0.6	0.4	0.9	1.1	1.1	1.7	<0.01	1.3
Mean	7.72	0.89	0.69	35.8	91.0	19.3	8.7	308	6.01	30.6
Mean AbsDif†	0.04	0.03	0.02	1.84	4.12	0.84	0.64	13.52	0.39	0.77

† Mean AbsDif: mean absolute difference

of 74.0 demonstrating high proficiency in detecting differences between wells. The lower ratios are for pH and total hardness of water whereas the highest ratio value is for NO_3-N. The mean of absolute differences between the duplicated pairs of samples was 0.04 for pH, 0.03 for SAR, 0.02 dS/m for EC, and 1.84, 4.12, 0.84, 0.64, 13.52, 0.39, and 0.77 ppm for Na, Ca, Mg, K, total hardness, NO_3, and S, respectively. The repeatability statistics were not calculated for micronutrients because of the high frequency of the concentration being below the reliable detection level.

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