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Evaluation of methods to determine residual soil nitrate zones across the northern Great Plains of the USA

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Abstract A four-year study was conducted from 2000 to 2004 at eight field sites in Montana, North Dakota and western Minnesota. Five of these sites were in North Dakota, two were in Montana and one was in Minnesota. The sites were diverse in their cropping systems. The objectives of the study were to (1) evaluate data from aerial photographs, satellite images, topographic maps, soil electrical conductivity (EC_a) sensors and several years of yield to delineate field zones to represent residual soil nitrate and (2) determine whether the use of data from several such sources or from a single source is better to delineate nitrogen management zones by a weighted method of classification. Despite differences in climate and cropping, there were similarities in the effectiveness of delineation tools for developing meaningful residual soil nitrate zones. Topographic information was usually weighted the most because it produced zones that were more correlated to actual soil residual nitrate than any other source of data at all locations. The soil EC_a sensor created better correlated zones at Minot, Williston and Oakes than at most eastern sites. Yield data for an individual year were sometimes useful, but a yield frequency map that

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combined several years of standardized yield data was more useful. Satellite imagery was better than aerial photographs at most locations. Topography, satellite imagery, yield frequency maps and soil EC_a are useful data for delineating nutrient management zones across the region. Use of two or more sources of data resulted in zones with a stronger correlation with soil nitrate.

Keywords Nitrogen · Management zone · Imagery · Topography · Electrical conductivity (EC_a) · Yield mapping

Introduction

Nitrate (NO_3) is variable in the soil and its distribution within farm fields can be spatially structured (Tabor et al. 1985; White et al. 1987; Karlen et al. 1996; Stevenson and Kessel 1996). Soil nitrate levels are also variable over time through movement with water and transformation by microorganisms. Although levels of NO_3-N change over time, their relative distribution occurs in spatially predictable patterns within fields (Franzen et al. 1998). This information can be exploited to identify management zones for precision nitrogen management (Franzen et al. 1998; Hornung et al. 2006; Long and Pierce 2010). Soil sampling density should be related to the scale of variation in the attribute of interest (Pierce and Nowak 1999). Nutrient management zones are used to direct variable-rate N application because the scale of fertilizer application equipment is often too large for more localized application. Most variable-rate fertilizer applicators have spread boom widths of 18–24 m. Given that the distance between applicator rate changes depending on vehicle speed is at least 100 m, the practical area of application to a specified rate is at least 0.2 ha, which is within the scale of nitrogen management by zone (Fulton et al. 1999). Sources of data that can be used to create management zones include electrical conductivity (EC_a) sensors, satellite and aerial imagery and yield monitors.

Sudduth et al. (2003) used EC_a measurements to measure depth to a limiting soil layer directly and to determine differences in clay content. This information was useful for identifying management zones for nutrient management. Heiniger et al. (2003) showed that the measurement of EC_a was an integration of several soil factors, including texture, cation exchange capacity and organic matter content. The measurements were useful for delineating nutrient management zones, but were not related directly to nutrients (Shaner et al. 2008). Satellite imagery has been used to delineate nutrient management zones (Bhatti et al. 1991; Franzen, 2004). Aerial photographs and other high resolution imagery might also have a role in delineating zones (Song et al. 2009). Nutrient management zones have also been derived from yield maps (Mulla and Bhatti 1997); however, several studies have concluded that use of multiple years of yield data would enable better nutrient management zones to be created (Blackmore 2000; Taylor et al. 2001).

Land surface features, or topography, can result in more accumulation of soil organic matter in lower landscape positions than upper landscape positions (Stevenson and Kessel 1996; Cassel et al. 1996; Kravchenko and Bullock 2000). In addition, as a determinant of soil water content and yield potential, topography affects the relationship of soil organic matter to N mineralization and the release of nutrients to crops (Pennock et al. 2001). Topography is related to residual soil nitrate patterns in the northern Great Plains of North America (Franzen et al. 1998), and has been used for N management in Canada (Becki et al. 1997; Pennock et al. 2001).

Objectives

Data to delineate zones are often evaluated in a few selected fields within a small region (Hornung et al. 2006) or concentrated on a single field. In this study, the available data were evaluated in fields across the Northern Great Plains region from Minnesota to Montana.

The objectives of this study were to (1) evaluate aerial photographs, satellite images, topography, EC_a and several years of yield data for delineating residual soil nitrate zones and (2) determine whether the use of data from several sources or from a single source is better to delineate nitrogen management zones by a weighted method of classification.

Materials and methods

A total of eight field sites were established across the northern Great Plains with five sites in North Dakota, two in Minnesota and one in Montana. A summary of site locations is given in Table 1. Grid sampling was used to characterize the spatial distribution of residual soil nitrate within each field. Specifically, soil samples were obtained by coring to a depth of 120-cm at the beginning of the study and in subsequent years prior to fertilizer application. The density of grid sampling ranged from one sample per 0.1–0.2 ha. Aerial photography was taken in 2001 and 2002 at an altitude of 1520 m above the soil surface in the nadir (directly above the point on the ground, perpendicular to the tangent) using Ektochrome color film. Satellite imagery was obtained from Landsat 5 from 2001 to 2003 during a time in the growing season where ground cover was almost complete, but the wheat, corn or sunflower crops were not yet in flower. Apparent EC measurements were made at each site during either 2001 or 2002 using a Veris® 3100 cart (Veris Technologies, Salina, KS), together with a Concord® GPS receiver with Garmin® WAAS differential receiver. The Veris cart was used either in the spring before seeding or in the autumn following harvest. Grain yield was measured using a mass flow, combine yield monitor. Barley biomass (Crookston) was determined by hand harvest of small plots and sugarbeet yield (Crookston and Renville) by machine harvest on a grid corresponding to the scale of soil sampling and other crop measurements. Yield frequency maps were made by standardizing and combining the data from more than one year (Franzen 2008). Topographic

Table 1 Summary of site information for the Northern Great Plains management zone experiments

Site	Longitude	Latitude	Rotation (years)
Valley City, ND	−97.91	46.87	Spring wheat, barley, sunflower,[a] 2001–2004
Oakes, ND	−98.11	46.05	Continuous corn, irrigated, 2002 and 2004
Mandan, ND	−100.93	46.76	Spring wheat, winter wheat, sunflower, 2001–2003
Minot, ND	−101.31	48.18	Canola, fallow, fallow, 2001–2003
Williston, ND	−103.78	48.12	Continuous spring wheat, dryland, 2002–2004
Malta, MT	−107.59	48.43	Spring wheat, fallow, 2001, 2003, 2004
Crookston, MN	−96.52	47.80	Barley, sugarbeet, 2001–2003
Renville, MN	−95.13	44.83	Corn, soybean, sugarbeet, 2002 (yields 2001–2003)

[a] Spring wheat *Triticum aestivum* L.; Barley *Hordeum vulgare*, Sunflower *Helianthus annuus* L.; Corn *Zea Mays* L.; Canola *Brassica napus* L.; Soybean *Glycine max* L. Merrill

maps were produced by measuring relative altitude using a laser-transit at each of the soil sample locations.

The image, yield frequency, EC_a and topographic data were delineated into zones based on classifying the data into five classes (quintals) for each data set as follows. First, these sets of spatially intensive data were transformed so that the measurements corresponded spatially to the soil nitrate sampling locations using the program Noesys© Transform. This program averages data around the required locations as directed into an n + 1 matrix or grid. Second, the averaged grid data were then entered into Surfer (Golden Software Co., Golden, CO) and classified into quintals. Third, the zones delineated in this way were superimposed on the nitrate data obtained from sampling the soil each year. Each zone was given a nitrate value representing the mean soil nitrate concentration from the sampling locations within the zone. The values for each soil nitrate map class (zone) were then correlated with the original nitrate values from the sampling grid within that zone.

At certain sites, combinations of nitrate estimates from the ancillary data sets yield frequency, EC_a, topography and imagery were compared with the original soil nitrate data. Each zone within each data set was rated 1–5, with 1 being the zone that has the smallest nitrate concentration in the data and 5 the zone with the largest. For each zone delimited by a given set of ancillary data, the correlation coefficient (r) was determined between the average nitrate value of the zone and the nitrate value at each sampling location. The nitrate value for the ancillary data set zone was then multiplied by the correlation coefficient associated with a given sampling location. This process was repeated for each set of ancillary data. The nitrate values weighted by the respective correlation coefficients were then added together. The resulting meta-values were correlated with the original nitrate values from the soil samples. The larger the correlation coefficient, the greater was the weight associated with a given set of ancillary data set, and vice versa.

Results and discussion

All correlations of zone residual nitrate with residual soil nitrate values are significant unless referred to in the discussion. The zone estimates of soil nitrate from ancillary data will be discussed in relation to the relative strength of correlation.

Valley City, ND

Maps of zones were developed at the Valley City site (12.5 ha) each year (2001–2004) from shallow soil EC_a data, topographic data, yield frequency data, and data from aerial photographs and satellite images obtained in 2002. The correlation of zone residual nitrate with the residual nitrate values from soil sampling (0.09-ha grid) is significant for all comparisons, except for zones developed using yield frequency in 2004 (Table 2). The correlation coefficients from the EC_a and yield frequency zone estimates are particularly weak, whereas those for topographic, aerial photograph and satellite imagery zone estimates of nitrate are stronger. In 2003, removal of N by the sunflower crop resulted in low residual nitrate over the entire field, which reduces the correlation between all zones and the relevant grid-sampled soil nitrate compared with other years. This phenomenon has also been observed in other studies following sunflower (Franzen et al. 1999) and sugarbeet crops (Franzen et al. 2000).

Combinations of data for delineating zones result in stronger correlations with the soil sample nitrate values than does any single set of data alone (Table 3). The strongest

Table 2 Correlation (r) between residual nitrate-N on the sampling grid with various zone estimates for the Valley City site, 2001–2004

Year	Crop	EC_a	Topography	Yield frequency (2001–2004)	Aerial photograph	Satellite imagery
2001	Barley	0.28	0.39	0.27	0.43	0.39
2002	Spring wheat	0.24	0.41	0.26	0.37	0.50
2003	Sunflower	0.16	0.30	0.21	0.23	0.25
2004	Spring wheat	0.20	0.30	0.12	0.33	0.30

Table 3 Correlation (r) between residual nitrate-N on the sampling grid with different combinations of data sets for the Valley City site, 2001–2003

Comparison	2001	2002	2003
Topography + EC_a	0.44	0.40	0.32
Topography + EC_a + Yield	0.50	0.46	0.38
Topography + EC_a + Satellite	0.49	0.45	0.37
Topography + Satellite + Yield	0.52	0.48	0.40

correlation for combinations examined is for topography, satellite imagery and yield frequency in 2001, Table 2.

Williston, ND

The Williston field (12.5 ha) was sampled for soil residual nitrate on a 0.27-ha grid. The majority of these correlations are weak (Table 4). Soil EC_a is correlated the most consistently with soil nitrate values, although the strongest correlation is for 2003 with the satellite image data. The correlation coefficients for satellite imagery in 2002 and 2004, however, are weak. Correlation coefficients below 0.21 were not significant.

Crookston, MN

The Crookston field is 16.8 ha in size and the soil was sampled for soil residual nitrate on a 0.28-ha grid. In 2001, the field was seeded to barley, but at harvest the field was too wet to combine due to excessive rainfall. Therefore, a total dry matter hand harvest was made that included the grain from areas of 0.56 m^2 on the same grid as that used to sample soil residual nitrate. An estimate of grain yield based on dry matter content was calculated and included in the yield frequency data.

Table 4 Correlation (r) between residual nitrate-N on the sampling grid with those for various zones for the Williston site, 2002–2004

Year	Yield frequency (2002–2004)	Topography	Aerial photograph (2002)	Satellite image (2002)	EC_a
2002	0.27	0.28	0.16	0.19	0.34
2003	0.29	0.18	0.23	0.47	0.22
2004	0.21	0.22	0.19	0.13	0.33

A map of soil nitrate values for 2001 is shown in Fig. 1. Zones delineated using an aerial photograph of the field in 2001 when the crop was barley, the satellite image for 2001, yield frequency developed from estimated yield for the 2001 barley crop and from the 2002 sugar beet harvest, soil EC_a and elevation data obtained in 2000 were compared with soil nitrate values from sampling each year (Fig. 2). The values mapped in Fig. 2 are correlated with those in Fig. 1, $r = 0.59$. The correlations between the different types of data used for zone delineation range from weak to strong, Table 5. Only the EC_a in 2001 was not significant. The strongest correlations with soil sampled nitrate values are for zones developed from topographic, EC_a and yield frequency data in 2002. The correlations are stronger for zones developed from topographic, EC_a, satellite and yield frequency data than when these data are used separately (Table 6).

Fig. 1 Soil nitrate concentration from sample data to 60 cm in depth, 2001 at Crookston, MN

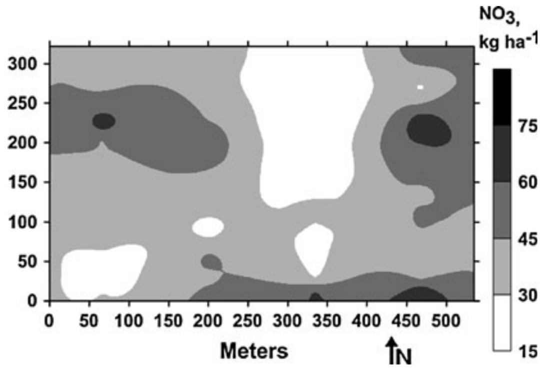

Fig. 2 Estimates of soil nitrate from zones delineated using a combination of topographic, EC_a and satellite image data, 2001 for Crookston, MN

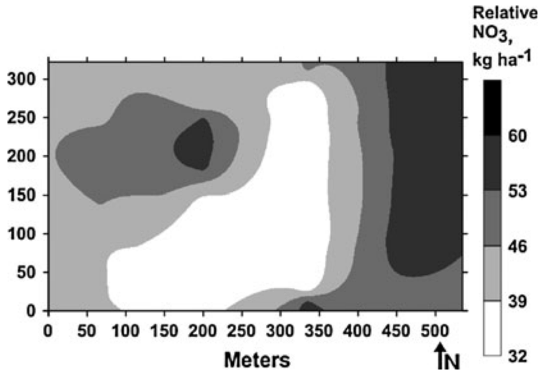

Table 5 Correlation (r) between residual nitrate–N on the sampling grid with various zone estimates for the Crookston site, 2001–2003

Year	Crop	Aerial photography	Satellite	Yield frequency (2001–2003)	EC_a	Topography
2001	Sugarbeet	0.32	0.53	0.32	0.10	0.53
2002	Barley	0.38	0.26	0.73	0.78	0.76
2003	Sugarbeet	0.31	0.61	0.31	0.26	0.44

Table 6 Correlation (*r*) between residual nitrate-N from sampling with different combinations of data sets for the Crookston site, 2001–2003

Year	Crop	Multi-layer data for zone delineation	
		Topography + EC_a + Satellite	Topography + Yield frequency + EC_a
2001	Sugarbeet	0.59	0.56
2002	Barley	0.79	0.79
2003	Sugarbeet	0.62	0.58

Oakes, ND

The Oakes site is a 17.6-ha area within a larger 64-ha pivot-irrigated field south of Oakes, ND. The soil nitrate-N sampling grid was 0.29 ha. The 2002 crop yield data only were available for investigation, although residual soil nitrate data were available for both 2002 and 2004. Both shallow and deep EC_a measurements are correlated with residual nitrate at this site (Table 7). Residual nitrate estimates from zones developed using topography, shallow EC (SEC) and deep EC (DEC) are the most strongly correlated with the soil sampled residual nitrate, albeit the correlations are weak. All other types of zone delineation data are even more weakly correlated with soil residual nitrate. Correlation coefficients with values below 0.3 are not significant.

Renville, MN

The Renville site is an 8.8-ha field that was sampled for soil residual nitrate on a 0.09-ha grid. Soybean biomass in 2001 and corn biomass in 2002 were estimated by hand sampling an area of 0.85 m^2 on the same grid as soil residual nitrate was measured. These measurements, in addition to sugarbeet yield data for 2003, were used to produce yield frequency data. Aerial photographs and satellite imagery were obtained in July 2003 when the crop was sugar beet. Soil nitrate levels were measured on soil samples obtained after the 2002 corn harvest.

The correlation between zones developed from yield frequency, topographic and aerial photograph data are weak, but a little stronger than for EC_a and the satellite image (Table 8). Correlation coefficients less than 0.25 were not significant. Zones developed from several types of data are only very slightly more correlated than for any single type of data (Table 9).

Table 7 Correlation (*r*) between sample residual nitrate–N and various zone estimates for the Oakes site, 2002 and 2004

Year	Yield 2002	Topography	Aerial photograph, 2002	Satellite image, 2002	SEC	DEC
2002	0.12	0.43	0.24	0.37	0.34	0.46
2004	0.06	0.23	0.16	0.13	0.33	0.43

SEC shallow EC_a, *DEC* deep EC_a

Table 8 Correlation (r) between residual nitrate-N on the sampling grid with various zone estimates for the Renville site, 2001-2004

Yield frequency (2001–2003)	Topography	Aerial photograph (2002)	Satellite image (2002)	EC_a
0.26	0.28	0.32	0.16	0.17

Table 9 Correlation (r) between residual nitrate-N on the sampling grid with different combinations of data sets for the Renville site, 2002

Topography + Yield Frequency + Satellite	Topography + Yield Frequency + EC_a
0.33	0.33

Montana

The two Montana sites are each 18.7-ha fields and both were in a spring wheat-fallow cropping system. Sampling for soil residual nitrate in 2001 and 2003 was on a 0.26-ha grid. The field was soil sampled on a 0.42-ha grid in 2004. The West field was in wheat in 2001 and 2003 and the East field was in wheat in 2002 and 2004. Soil nitrate was not measured in the East field in 2002; therefore correlations with the zone delineation data are available only for 2004 at this site. Residual nitrate ranged from 9 to 14 kg ha^{-1} in 2001 and 2002, respectively, at the 0–60 cm depth. When the variation in residual nitrate is small such as here, correlations with zones are usually weak (Franzen et al. 1999). Accordingly, the correlations for the relationship between soil nitrate and each type of data for zone delineation are <0.35 (Table 10). In the West field, nitrate estimates from zones based on topography are the most strongly correlated with the sample nitrate data in 2003 and in 2004. Landsat 5 satellite zones are the most strongly correlated with soil nitrate values in 2001. The IKONOS (Commercial imagery satellite operated by GeoEye, Inc., Dulles, VA) satellite imagery zones are the least correlated of any type fo data for zone delineation. Soil EC_a and yield frequency zones from 2002 to 2004 yield data are very weakly correlated with soil nitrate data for any year (Table 10). Correlation coefficients less than 0.23 are not significant.

In 2001, zones developed from a combination of either topography–satellite image–EC_a or topography–satellite image–yield frequency data result in stronger correlations than any single type of data alone. However, multiple data layers do not increase the correlations in 2003 (Table 10).

Table 10 Correlation (r) between residual nitrate-N on the sampling grid with various zone estimates for the Montana site, 2001, 2003–2004

Site	EC_a	Topo	YF	Aerial	Satellite[a]	Topo–EC–YF	Topo–Sat–EC	Topo–Sat–YF
West, 2001	0.19	0.19	0.06	0.18	0.24	–	0.35	0.32
West, 2003	0.14	0.31	0.16	0.18	0.21	–	0.03	0.18
East, 2004	0.03	0.26	0.15	NA	0.01	0.21	–	–

Topo topography, *YF* yield frequency

[a] Landsat 5 2001-2002, IKONOS 2004

Mandan, ND

The Mandan site was divided into three fields, designated I4 (West), I5 (Center) and I6 (East). The I4 field is about 4 ha; the I5 and I6 fields are both about 6 ha each. The I4 field was sampled on a 0.2-ha grid in 2001, I5 was sampled on a 0.2-ha grid in 2003 and I6 was sampled on a 0.1-ha grid in 2002. Correlation coefficients below 0.22 were not significant (Table 11). Topography and EC_a are moderately correlated with soil nitrate data for I4 in 2001, and yield frequency and the satellite image (Landsat 5) strongly so (Table 11). The correlations for I6 in 2002 are weak for all types of data. In 2003 for I5, topography aerial imagery, the satellite image and EC_a are moderately correlated with soil nitrate data. Correlation coefficients less than 0.25 are not significant. Zones from several layers of data were not explored at this site.

Minot, ND

The Minot site is about 2.7 ha in size and the soil was sampled on a 0.13-ha grid in 2001, 2002 and 2003. In 2000, the field was in canola and yield was recorded. The field was fallow during 2002 and 2003. The ancillary data used in the delineation of zones resulted in maps of nitrate values with a similar pattern to that from the soil nitrate data (Fig. 3). Correlation coefficients (r) of soil nitrate estimates in Fig. 3 for topography, EC_a, satellite image and a combination of topography, EC_a and satellite data are 0.49, 0.33 (NS), 0.62, and 0.67, respectively. Nitrate values based on zones delineated by topography are the most consistently correlated with the soil nitrate values for all three years (Table 12). The yield data of the canola field from 2001 are the least correlated of all types of data in 2002 and 2003. Use of topography–satellite–EC_a data to delineate zones resulted in the strongest correlation with soil nitrate. Correlation coefficients with values less than 0.4 are not significant.

Table 11 Correlation (r) between residual nitrate-N on the sampling grid with various zone estimates for the Mandan site, 2001–2003

Year/field	Yield frequency	Topography	Aerial photograph (2002)	Satellite image (2002)	EC_a
2001/I4	0.82	0.47	0.18	0.78	0.51
2002/I6	0.21	0.37	0.13	0.25	0.16
2003/I5	0.11	0.44	0.51	0.39	0.41

Table 12 Correlation between residual nitrate-N on the sampling grid with various zone estimates for the Minot site, 2001–2003

Year	Correlation (r)					
	Yield	Topography	EC_a	Aerial photograph	Satellite image	Topography–Satellite–EC
2001	0.60	0.49	0.33	0.46	0.62	0.67
2002	0.25	0.44	0.68	0.33	0.25	0.75
2003	0.16	0.59	0.34	0.44	0.52	0.72

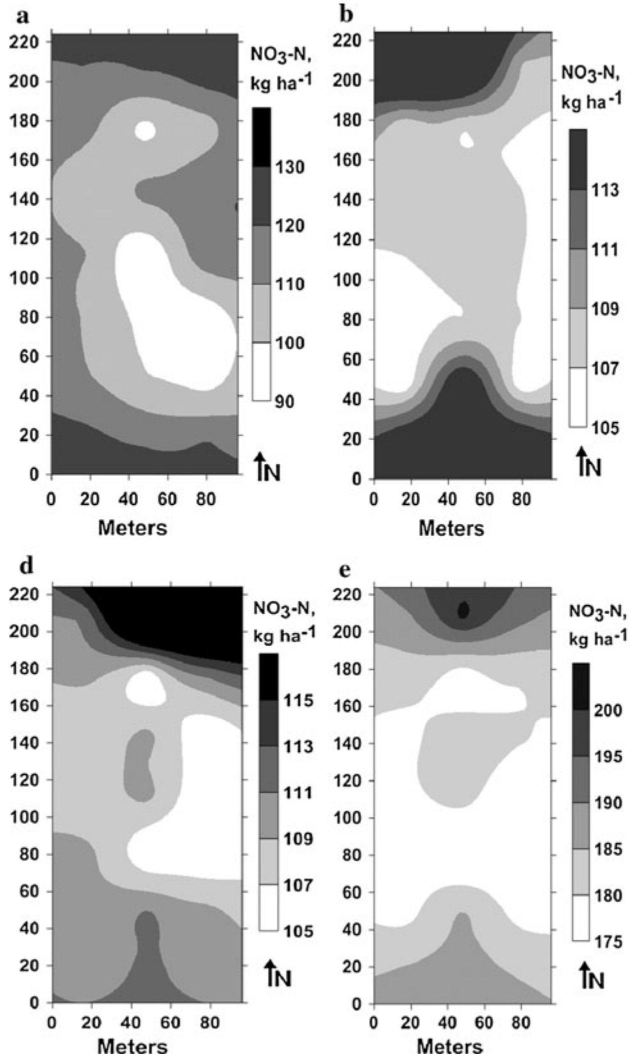

Fig. 3 **a** Nitrate estimates from soil sample data, compared with nitrate estimates from zones based on: **b** topography, **c** EC_a, **d** satellite image and **e** a combination of topographic, EC_a and satellite data for Minot, ND

Summary

Correlations determined between the original soil nitrate data within each field and the nitrate estimates produced by the zones showed that topography was the most consistently correlated variable with 18 significant comparisons out of 22 possible comparisons. Topography also tended to result in stronger correlations than the other variables, with 10 correlations >0.4. Soil EC_a was significantly correlated in 15 of 24 comparisons, with 6 correlations >0.4. Satellite imagery was significantly correlated in 15 of 22 comparisons with 7 correlations >0.4. Aerial photographs were significantly correlated in 11 of 21 comparisons, with 4 correlations >0.4, and correlation with yield frequency data was significant for 10 out of a possible 22 comparisons, with 3 correlations >0.4.

The EC_a was the most useful ancillary data at Valley City and Oakes, North Dakota where there are large areas of coarser-textured soil. It was significantly correlated in 8 of 8 comparisons at these two sites, although the relationship between EC_a and soil sample nitrate was weaker at Valley City than at Oakes, and shallow EC_a was weaker at Oakes than was deep EC_a. In the drier areas farther west, EC_a predicted soil nitrate values inconsistently. At the sites near Mandan and Minot, North Dakota, EC_a was correlated with nitrate in some years, but not at the site near Malta, Montana. In Minnesota, EC_a was useful in 2 of the 3 years at Crookston, which has a considerable area of sand and a large concentration of soluble salts (data not shown), but EC_a was not correlated at Renville, MN. The correlation between EC_a nitrate zone estimates and soil sample nitrate values was particularly strong at Crookston in 2002.

Yield or yield frequency zones were significantly correlated at Crookston, Renville and Valley City, but generally the relationships were weak. Yield was only correlated at Minot when the crop was canola, but the relationship that year was strong. Yield or yield frequency zones were not correlated at Minot in the two subsequent years. Yield of corn at Oakes was very uniform; therefore zone delineation by yield frequency at this site was poor.

Satellite imagery was significantly correlated in all years at Valley City, Crookston, Mandan and Minot. In some years the correlations were very strong, but in others the relationship was weaker such as at Montana, Oakes and Williston.

Although zones derived from aerial photographs were better correlated over all data sets compared to yield frequency, the practicality of aerial photographs as a data source will be limited by the lack of commercial providers. Given the ready availability of satellite imagery, the logistics of planning aerial photography is questionable under current market conditions. In addition, the correlations between soil nitrate data and estimates from aerial photography zones tended to be weak albeit significant.

It is clear from the comparisons that no single data source can delineate management zones consistently in all fields. Topographic data were the best, but even these data resulted in weak relationships with soil nitrate values at some locations. On the other hand, by combining data such as topography, EC_a, yield frequency and satellite imagery moderate or strong correlations between soil nitrate and estimated nitrate from the combined data zones resulted in 25 of the 28 comparisons. The zones produced by several types of data were more strongly correlated in terms of nitrate comparisons than was any single set of data. Topography, satellite imagery, yield frequency and soil EC_a sensors were useful for delineating nutrient management zones across the region.

Conclusions

The outcome of the study in North Dakota, Minnesota, and Montana to compare soil nitrate within fields with estimated soil nitrate from zones delineated by topography, satellite imagery, aerial photography, yield maps or field frequency maps and soil EC_a is that:

- Topography, satellite imagery, aerial photography, yield maps or yield frequency and soil ECa were useful throughout the region for identifying zones that represented patterns of variation in residual soil nitrate, and which could be used to formulate N fertilizer recommendations.

- None of the delineation methods consistently produced strongly correlated zones in all years.
- Use of combinations of ancillary data for zone delineation resulted in stronger correlation and more strongly correlated zones than any one method alone.

The often weak correlations between zone delineation estimates of nitrate and the soil sample nitrate data are related most often to the variation in soil nitrate within the zones. Although zone management of N is an improvement in many fields from a single N rate strategy, the study reveals that in the future additional improvements will need to come from strategies that use, as yet undeveloped, methods for inexpensive small spatial scale soil analysis or early-season plant nutrient sensors.

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