Delineating Nitrogen Management Zones in a Sugarbeet Rotation Using Remote Sensing - A Review

D.W. Franzen

North Dakota State University, Box 5758, Fargo, ND 58105

ABSTRACT

In 2002, twenty percent of the sugarbeet area in the Red River Valley of Minnesota and North Dakota was examined using satellite imagery for the purpose of modifying nitrogen (N) recommendations for subsequent crops. N was applied to sugarbeet (*Beta vulgaris L.*) after soil sampling in patterns delineated by previous satellite images. The use of this technology was based on over one hundred years of nitrogen research, and clever use of the principles established over generations of research combined with new capabilities in a computerized and space-age world. A review of the research basis for the use of satellite imagery to manage N in a sugarbeet rotation and the advancements made towards the use of this technology is presented. A recent survey of sugarbeet growers shows an economic advantage of \$50 ha^{-1} and \$113 ha^{-1} for grid sample-based and zone sample-based N rates to sugarbeet. Even with the large database which shows the agronomic and economic advantages of site-specific N application to sugarbeet, general adoption of the techniques is still years away.

Additional Key Words: nitrogen, satellite imagery, soil sampling, precision agriculture

Nitrogen (N) management is important for most crops due to its effect on yield, input costs, and environmental concerns. N management is important in sugarbeet production for these same reasons, and also due to its effect on root quality. Sugarbeet requires N early in the season for root development. Later in the season, excessive N leads to reduced sucrose concentration of roots and increased levels of impurities, including nitrate and ammonium compounds, which reduce sucrose recovery at the refinery. Since 1973, growers in the Red River Valley have been paid on a formula which includes root yield delivered and extractable sucrose; sucrose content less loss to molasses.

The relationship between N, root yield and quality has been known for over one hundred years. The earliest examination of N effect on sugarbeet quality in the US was reported in Colorado by Headden (1912). However, Headden refers to even earlier European reports. Winner (1993) mentions an experiment station established in Bernburg, Germany in 1882 to investigate mineral nutrition of sugarbeet. Numerous studies have since been conducted to examine this relationship (Gardner and Robinson, 1942; Hill, 1946; Haddock, 1952; Hunter and Yungen, 1952; Schmehl et al., 1963 (Table 1); Baldwin and Stevenson, 1969; Boyd et al., 1970 (Table 2); Bauer and Cassel, 1972 (Table 3); Soine, 1973 (Table 4); Halvorson and Hartman, 1975).

Although in the middle of the twentieth century there was agreement regarding the effect of excessive N on the quality of sugarbeet, there was disagreement about how to manage N application.

Table 1. The effect of N rates on sugarbeet root yield, sucrose concentration and sucrose yield, Colorado (Schmehl et al., 1963).

N Rate, kg ha^{-1}	Root yield, Mg ha^{-1}	Sucrose concentration, %	Sucrose yield, Mg ha^{-1}
0	46.4	16.4	7.6
45	50.6	15.4	7.8
134	49.7	14.5	7.2

Table 2. Effect of nitrogen fertilizer on sucrose yield, United Kingdom (Boyd et al., 1970).

N rate, kg ha^{-1}	Sucrose yield, Mg ha^{-1}
0	5.67
45	6.28
90	6.79
135	6.88
180	6.80

Table 3. Effect of N application over three sugarbeet varieties on sugarbeet root yield, sucrose concentration, impurity index and sucrose yield, Oakes, ND (Bauer and Cassel, 1972).

N Rate kg ha-1	Root yield, kg ha-1	Sucrose concentration, %	Sucrose yield, Mg ha-1	Impurity index, ppm
0	48.8	17.0	8.3	429
56	50.0	16.7	8.3	482
112	54.0	16.4	8.9	534
224	55.1	15.3	8.4	750

Initial soil nitrate-N to 60 cm was 56 kg ha-1

Table 4. Effect of preplant N application on sugarbeet root yield, sucrose content and sucrose yield, Hillsboro, ND (Soine, 1972).

N Rate, kg ha-1	Root yield, Mg ha-1	Sucrose concentration, %	Sucrose yield, Mg ha-1
0	32.9	16.2	5.3
56	38.1	16.0	6.1
112	40.3	15.1	6.1
224	41.7	14.0	5.8

Initial residual nitrate-N to 60 cm was 50 kg ha^{-1}

Until the mid-1960's, it was believed that measurement of soil nitrate had little relationship with N availability to crops (Scarsbrook, 1965). However, Soper and Huang (1963) demonstrated that root zone nitrate levels were good indicators of the N needs of spring barley. By 1971, North Dakota State University was basing N fertilizer recommendations on residual fall soil nitrate testing (Torkelson, 1972). Subsequent studies confirmed the value of nitrate soil testing in many regions (James, 1971; James et al., 1971; Reuss and Rao, 1971; Roberts et al., 1972; Carter et al., 1975; Giles et al., 1975; Hills and Ulrich, 1976), so that by 1980, Moraghan states "soil testing, involving the determination of nitrate-N in the 0-2 foot soil zone, is widely practiced in the Red River Valley to estimate rates of application of N fertilizer." A number of studies that also included 60-120 cm nitrate-N determinations (Anderson et al., 1972; Rudolph et al., 1980) prompted a revision of recommendations to include the deeper

N as an adjustment (Cattanach and Dahnke, 1981). Subsequent studies (Moraghan, 1982, 1984, 1985, Franzen et al., 1999; Franzen et al.2002) confirmed the importance of identifying fields with high soil nitrate-N levels below 60 cm.

Crohain and Rixhon (1967) conducted a four year rotation study in France where sugarbeet tops were analyzed for N, incorporated into the soil, and a series of crops were grown in the following years. They concluded that the sugarbeet tops contributed 35-40 kg ha^{-1} N the year after incorporation. Draycott (1972) cited a similar study by Widdowson (1971, personal communication to Draycott) that indicated a N value of sugarbeet tops to a subsequent barley crop of about 20 kg ha^{-1}. Abshihi et al. (1984) conducted N tracer studies and determined that sugarbeet tops were directly contributing N to the subsequent crop. Moraghan and Anath (1985) noted that soil nitrate-N in the 0-15 cm depth was elevated, while deeper depths were depressed the year following a sugarbeet crop, suggesting that sugarbeet tops were being mineralized.

Once N requirements for maximum sugarbeet root growth are achieved, additional N increases top growth (Lamb and Moraghan, 1993). Moraghan and Etchevers (1975) refered to sugarbeet tops at one experimental site as having potential as an "excellent green manure crop" due to its high N content. Moraghan and Cattanach (1986) referred to sugarbeet canopies as "green" areas and "yellow" areas within fields, and observed heterogeneity of soil nitrate-N levels within sugarbeet fields corresponding to leaf color.

Moraghan and Smith (1994) began to make distinctions between sugarbeet tops with small or large amounts of N and the N benefits to subsequent crops. Sugarbeet tops with large amounts of N (7,600 kg ha^{-1} top weight containing 299 kg ha^{-1} N) resulted in wheat grain yields similar to a 132 kg ha^{-1} N fertilizer application. Sugarbeet tops with smaller amounts of N (4760 kg ha^{-1} top weight and 72 kg ha^{-1} N) resulted in a grain yield increase, equivalent to the grain yield increased by an application of about 45 kg ha^{-1} N fertilizer. The experiment was repeated (Moraghan and Smith, 1995a) with similar results. It was also reported (Moraghan and Smith, 1995b) that N was released from residues by mid-May, following fall incorporation of sugarbeet tops. This work was summarized in Moraghan and Smith (1996).

Smith (1996, 1997) conducted site-specific N application studies with sugarbeet in the rotation. When N fertilizer recommendations for crops following sugarbeet were based only on soil nitrate levels, variability patterns of soil N levels and soil nitrate-N content was similar at the end of the rotation to those found when the study began. He suggested that sugarbeet top N content should be considered to prevent excessive N application within the rotation.

Satellite imagery was used to distinguish between "high-N" and "low-N" tops in commercial fields (Moraghan and Horsager, 1996). Three reflectance bands (530-590 nm, 600-680 nm, and 780-890 nm) were used to form the image. The spatial resolution (30m) of the satellite images prevented identification of some ground truthed features. The authors suggested that sampling based on topography differences might improve the field information.

Moraghan et al. (1997) separated sugarbeet canopy color from images obtained from late August through early October into yellow, yellow-green, and green. Both aerial photography and satellite imagery were used to detect these canopy color differences at the twelve "green" sites, eight "yellow-green" sites and six "yellow" sites in six fields. Subsequent testing of the technique within grower fields (Moraghan, 1998; Moraghan, 1999, Sims et al., 2002) indicated that providing N credits to "green" sugarbeet tops was practical.

Franzen et al. (1999, 2000) used NDVI imagery from the Landsat 5 satellite to delineate zones for applying sugarbeet top credits against N recommendations for wheat. NDVI is an acronym for Normalized Differential Vegetative Index, which is the ratio of the reflectance of infrared minus red light, divided by infrared plus red light. NDVI is related to relative biomass, crop type, plant health and nutrition. Yields of areas where credits were given were similar to yields in areas where credits were not needed. Careful attention to N application rates to crops within the rotation, directed by soil sampling, application of N, and sugarbeet top N credits within these image-based zones, resulted in improved sugarbeet quality.

In 2002, approximately 40,000 ha (about 20% of the 2002 sugarbeet acreage in the Red River Valley) of crops immediately following sugarbeet were given a credit based on this research, with a reduction in fertilizer costs of about \$20 ha^{-1}. Other benefits included reduced lodging of small grains and lower residual N levels in fields returning to sugarbeet in two to three years.

The sugarbeet cooperatives purchase NDVI imagery (Landsat 5) of the entire Red River Valley during August and September. In some years, clouds obscure some areas, but in most years at least one image is available for use. Agriculturalists with the sugar cooperatives and private consultants help growers create application maps from the imagery, using the research described previously. Growers pay a small fee (about \$4.50 ha^{-1}) for this service. After an image is created, a field within the image is scouted to identify green and yellow areas as compared to higher and lower vigor canopies as shown in the NDVI image.

Table 5. Comparison of correlation coefficients between NDVI readings of sugarbeet canopy and the product of NDVI multiplied by canopy height for canopy dry matter, canopy N content, and total N.

Comparison	NDVI	NDVI x Canopy height
		r
Dry matter	0.395	0.692
N concentration	0.546	0.811
Total N	0.507	0.572

Once the satellite NDVI image is received, the field is divided into three or more zones, depending on the wishes of the grower, and an application map is produced using ground truthed canopy color and associated N credits. "Green" canopies receive 90 kg ha^{-1} credit against the N requirements of the subsequent crop, and "yellow" canopies receive 0 kg ha^{-1} N credit. The intermediate zones receive an appropriate credit in a linear relationship based on the number of zones.

The field correlation visit is necessary because of the two-dimensional nature of the satellite image. Leaf canopy of sugarbeet has depth as well as width and includes plant materials not seen by the satellite. One weakness of satellite imagery is its inability to estimate biomass in tall, dense canopies. Using a hand-held NDVI sensor (Greenseeker® , N-Tech Industries, Inc.) 150 readings were made in a 12.5 ha sugarbeet field (Franzen et al., 2004) (Table 5). At the point of each set of NDVI measurements, conducted on a 3 m length of row, top height measurements were also made. Including canopy height increased the correlation of imagery with dry matter, N content, and total N of the canopy. In this study, a three-dimensional volume estimate was related to N credits more strongly than using imagery alone.

Soil sampling is generally not used after sugarbeet when using the satellite imagery N credit system, because soil nitrate-N levels are very small after sugarbeet production. When unusually tall, green sugarbeet areas are encountered, soil testing is sometimes conducted to further modify recommendations for the subsequent crop (Franzen et al., 2002).

Growers are also beginning to use their sugarbeet imagery to direct soil sampling prior to their next sugarbeet crop. Rotations influence nitrogen available to sugarbeet (Nuckols, 1938; Stockinger et al., 1963; James, 1971, Shock et al., 2000). Winter (1984) identified cropping systems capable of reducing excessive soil nitrate-N before sugarbeet. However, most growers are tied economically to a rotation and must manage N within that framework. Franzen et al. (1998, 2000) has

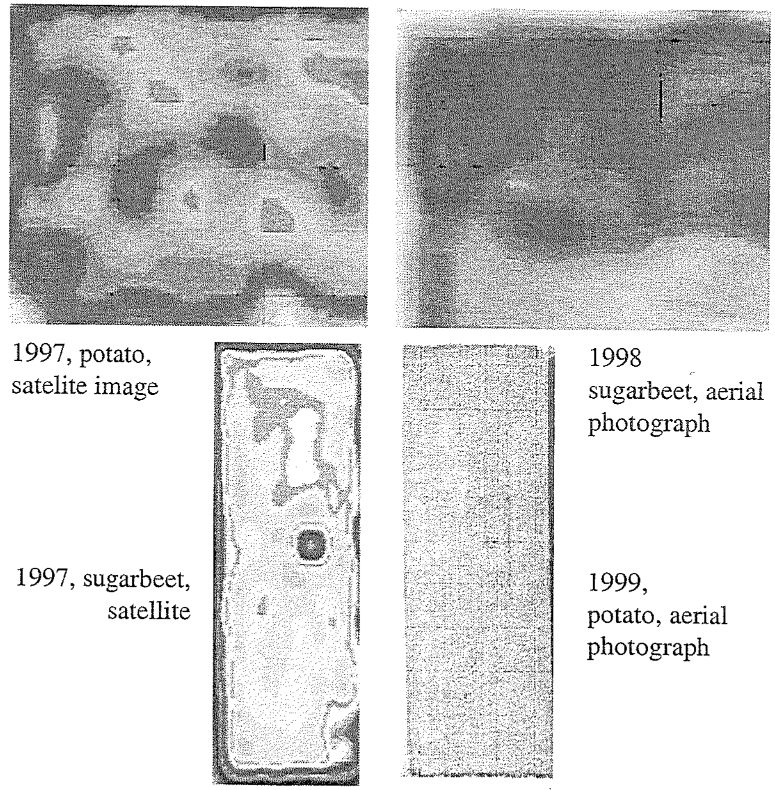

Fig. 1. Comparison of imagery of two fields between years. Patterns in each field are similar when different years and crops are compared.

shown that N management zones are relatively stable between years (Figure 1). Because of this stability, sugarbeet imagery could be expected to help delineate N management zones throughout the rotation, including areas to sample for the following sugarbeet crop.

Zone soil testing in the Red River Valley using satellite image to help delineate nitrogen management zone boundaries has increased from zero in 1997 to about 9,000 ha in 2002 (American Crystal Sugar survey, 2003). A survey of growers suggests an economic advantage for those using a zone soil testing approach prior to sugarbeet (Figure 2). Currently, studies are being conducted to determine whether imagery combined with other delineation methods would provide better direction for soil sampling than imagery alone.

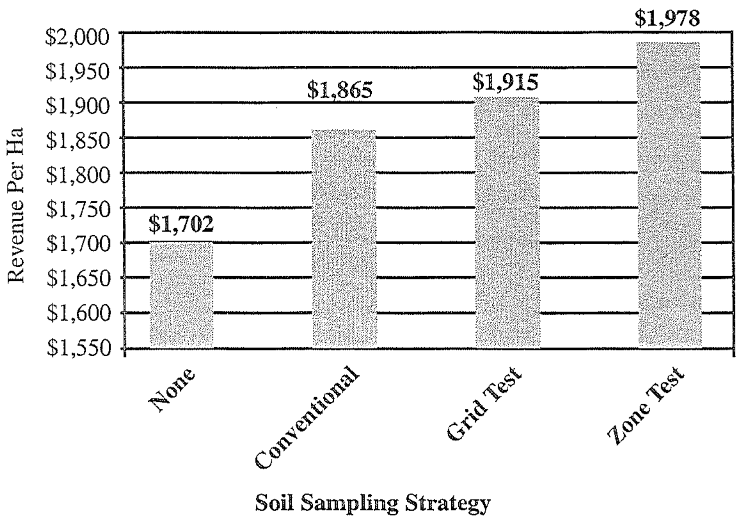

Fig. 2. Sugarbeet revenue per hectare between soil sampling practices, 5-year summary, American Crystal Sugar, Moorhead, MN. Internal survey, 2003.

SUMMARY

Imagery is now considered an important tool for sugarbeet N management. Beginning with the sugarbeet crop, imagery is used to provide N credits for the following crop. The secondary crop is grown, and imagery from the sugarbeet crop, and perhaps another layer of data, such as topography, yield mapping, or soil EC, is used to direct soil sampling on the secondary and tertiary crops in the rotation. That same delineation can then be used to direct the soil sample for nitrates to a 120 cm depth prior to the sugarbeet crop N application.

For imagery to be used to successfully modify N application to any crop, a substantial data base is needed to describe the relationship between the crop, nutrition, and imagery. Once this relationship is established and accepted, the industry, research and outreach communities need to put the information into recommendations and encourage acceptance by growers. Even with the enormous amount of research and outreach effort to date in sugarbeet production, the industry is still a long way away from full acceptance of using imagery to manage N in a sugarbeet rotation, although it has made remarkable progress in just ten years.

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LITERATURE CITED

Abshihi, A., F.J. Hills, and F.E. Broadbent. 1984. Nitrogen utilization by wheat from residual sugarbeet fertilizer and soil incorporated sugarbeet tops. Agron. J. 76:954-958.

Anderson, F.N., G.A. Peterson, and R.A. Olson. 1972. Uptake patterns of ^{15}N tagged nitrate by sugarbeets as related to soil nitrate level and time. J. Amer. Soc. Sugar Beet Technol. 17:42-48.

Baldwin, C.S. and C.K. Stevenson. 1969. The effect of nitrogen on yield, percent sucrose, and clear juice purity of sugarbeets. J. Amer. Soc. Sugar Beet Technol. 15:522-527.

Bauer, A., and K. Cassel. 1972. Soil management research-Oakes 1971. 1971 Sugarbeet Res. and Ext. Rep., North Dakota State Univ. Ext. Ser. 2: 49-56. (www.sbreb.org)

Boyd, D.A. Tinker, P.B.H., Draycott, A.P., and Last, P.J. 1970. Nitrogen requirement of sugar beet grown on mineral soils. J. Agric. Sci., Camb. 74:37-46.

Carter, J.N., D.T. Westermann, M.E. Jensen, and S.M. Bosma. 1975. Predicting nitrogen fertilizer needs for sugarbeets from residual nitrate and mineralizable nitrogen. J. Am. Soc. Sugar Beet Technol. 18:232-244.

Cattanach, A.C. and W.C. Dahnke. 1981. Fertilizing sugarbeets. SF-714. 1980 Sugarbeet Res. and Ext. Rep., North Dakota State Univ. Ext. Serv. 11: 73-76. (www.sbreb.org)

Crohain, A. and L. Rixhon. 1967. Practical fertilizer value of sugarbeet tops (La valeur fertilisante pratique des feuilles et collets de betterave sucriere). Bulletin of recherches agronomiques de Gembloux. Vol. 2:397-428.

Draycott, A.P. 1972. Sugar-Beet Nutrition. John Wiley & Sons, NY. 250 pp.

Franzen, D.W. 2000. Profitability of variable-rate N application to wheat. 1999 Sugarbeet Res. and Ext. Rep., North Dakota State Univ. Ext. Serv. 30: 127-131. (www.sbreb.org)

Franzen, D.W., L.J. Cihacek, V.L. Hofman, and L.J. Swenson. 1998. Topography-based sampling compared with grid sampling in the northern Great Plains. J. Prod. Agric. 11:364-370.

Franzen, D.W., L. Reitmeier, J.F. Giles, and A.C. Cattanach. 1999. Aerial photography and satellite imagery to detect deep soil N levels in potato and sugarbeet. p. 281-290. In P.C. Robert et al. (ed.). Precision Agriculture, Proceedings of the 4th International Conference, 19-22 July, 1998, St. Paul, MN. ASA, CSSA, SSSA, Madison, WI.

Franzen, D.W., A.J. Landgraff, J.F. Giles, N.R. Cattanach, and L.J. Reitmeier. 2000. Nitrogen availability and movement within wheat fields following sugarbeet. 1999 Sugarbeet Res. and Ext. Rep., North Dakota State Univ. Extension Serv. 30: 117-126. (www.sbreb.org)

Franzen, D.W., J.F. Giles, L.J. Reitmeier, A.J. Hapka, N.R. Cattanach, and A.C. Cattanach. 2002. Summary of four years of research on poor quality sugarbeets in a sugarbeet, spring wheat, potato rotation. 2001 Sugarbeet Res. and Ext. Rep., North Dakota State Univ. Ext. Serv. 32:152-173. (www.sbreb.org)

Franzen, D.W., G. Wagner, and A. Sims. 2004. Application of a ground-based sensor to determine N credits from sugarbeet.. 2004 Sugarbeet Res. and Ext. Rep., North Dakota State Univ. Ext. Serv. 34: 119-123. (www.sbreb.org)

Gardner, R. And D.W. Robertson. 1942. The nitrogen requirement of sugar beets. Colorado. Agr. Exp. Sta. Tech. Bull. 28.

Giles, J.F., J.O. Reuss, and A.E. Ludwick. 1975. Prediction of nitrogen status of sugarbeets by soil analysis. Agron. J. 67;454-459.

Haddock, J.L. 1952. The nitrogen requirement of sugar beets. Proc. Am.. Soc. of Sugar Beet Technol. 7: 159-165.

Halvorson, A.D. and G.P. Hartman. 1975. Long-term nitrogen rates and sources influence sugarbeet yield and quality. Agron. J. 67:389-396.

Headden, W.P. 1912. Deterioration in the quality of sugarbeets due to nitrates formed in the soil. Colorado Agr. Exp. Sta. Bull. 183. 179 p.

Hill, K.W. 1946. Yield, percentage of sucrose and coefficients of apparent purity of sugar beets as affected by rotational, manurial, and fertilizer practices at the Dominion Experiment Station, Lethbridge, Alberta. Proc. Am. Soc. Sugar Beet Technol. 4: 63-72.

Hills, F.J. and A. Ulrich. 1976. Soil nitrate and the response of sugarbeets to fertilizer nitrogen. J. Amer. Soc. Sugar Beet Technol. 19:118-124.

Hunter, A.S. and J.A. Yungen. 1952. The responses of sugar beets to fertilizers, spacing, and irrigation on eastern Oregon soils. Proc. Am. Soc. Sugar Beet Technol. 7: 180-188.

James, D.W. 1971. Soil fertility relationships of sugarbeets in central Washington: Nitrogen. Washington Agri. Exp. Sta. Tech. Bull. 68.

James, D.W., A.W. Richards, W.H. Weaver, and R.L. Reeder. 1971. Residual soil nitrate measurement as a basis for managing nitrogen fertilizer practices for sugarbeets. J. Am. Soc. Sugar Beet Technol. 16:313-322.

Lamb, J.A. and J.T. Moraghan. 1993. Comparisons of foliar and preplant applied nitrogen fertilizer for sugar beet. Agron. J. 85:290-295.

Moraghan, J.T. 1980. Sugar production and soil nitrate. 1979 Sugarbeet Res. and Ext. Rep., North Dakota State University Extension Service 10:119-133. (www.sbreb.org)

Moraghan, J.T. 1982. The influence of residual deep soil nitrate on sugarbeet production. J. Amer. Soc. Sugar Beet Technol. 21:362-373.

Moraghan, J. 1984. Soil fertility research. 1983 Sugarbeet Res. and Ext. Rep., North Dakota State Univ. Ext. Serv. 14: 93-106. (www.sbreb.org)

Moraghan, J. 1985. Nitrogen studies with sugarbeets. 1984 Sugarbeet Res. and Ext. Rep., North Dakota State Univ. Ext. Serv. 15: 86-96. (www.sbreb.org)

Moraghan, J.T. 1998. Testing a new precision farming technique involving sugarbeet tops in growers= fields. 1997 Sugarbeet Res. and Ext. Rep., North Dakota State Univ. Ext. Serv. 28:120-126. (www.sbreb.org)

Moraghan, J.T. 1999. A successful application of a new precision farming technique by a sugarbeet grower. 1998 Sugarbeet Res. and Ext. Rep., North Dakota State Univ. Ext. Serv. 29: 113-117. (www.sbreb.org)

Moraghan, J.T. and S. Ananth. 1985. Return of sugarbeet tops and the accumulation of certain chemical constituents in soil. J. Am. Soc. Sugar Beet Technol. 23:72-79.

Moraghan, J.T. and A.C. Cattanach. 1986. Foliar nitrogen fertilization of sugarbeets. 1985 Sugarbeet Res. and Ext. Rep., North Dakota State Univ. Ext. Serv. 16.78-82. (www.sbreb.org)

Moraghan, J.T. and J. Etchevers. 1975. Soil fertility investigations in the Red River Valley. 1974 Sugarbeet Res. and Ext. Rep., North Dakota State Univ. Ext. Ser. 5: 64-76. (www.sbreb.org)

Moraghan, J.T. and K. Horsager. 1996. Yield variability in sugarbeet fields. 1995 Sugarbeet Res. and Ext. Rep., North Dakota State Univ. Ext. Ser. 26: 138-146. (www.sbreb.org)

Moraghan, J.T. and L.J. Smith. 1994. Influence of sugarbeet tops on growth of a subsequent wheat crop. 1993 Sugarbeet Res. and Ext. Rep., North Dakota State Univ. Ext. Ser. 24:262-272. (www.sbreb.org)

Moraghan, J.T. and L.J. Smith. 1995a. Influence of sugarbeet tops on growth of wheat in 1994. 1994 Sugarbeet Res. and Ext. Rep., North Dakota State Univ. Ext. Ser. 25:199-208. (www.sbreb.org)

Moraghan, J.T. and L.J. Smith. 1995b. Early season release of inorganic nitrogen from sugarbeet tops. 1994 Sugarbeet Res. and Ext. Rep., North Dakota State Univ. Ext. Ser. 25: 209-214. (www.sbreb.org)

Moraghan, J.T. and L.J. Smith 1996. Nitrogen in sugarbeet tops and the growth of a subsequent wheat crop. Agron. J. 88:521-526.

Moraghan, J.T., K. Horsager, L. Smith, A. Sims, and J. Holland. 1997. Canopy reflectance and GPS technology in relation to sugar production. 1996 Sugarbeet Res. and Ext. Rep., North Dakota State Univ. Ext. Ser. 27:121-133. (www.sbreb.org)

Nuckols, S.B. 1938. The effect of rotations and manure upon sugar beets. Proc. Amer. Soc. Sugar Beet Technol. 1:25-28.

Reuss, J.O. and P.S.C. Rao. 1971. Soil nitrate nitrogen levels as an index of nitrogen fertilizer needs of sugarbeets. J. Am. Soc. Sugar Beet Technol. 16:461-470.

Roberts, S., A.W. Richards, M.G. Day, and W.H. Weaver. 1972. Predicting sugar content and petiole nitrate of sugarbeets from soil measurements of nitrate and mineralizable nitrogen. J. Am. Soc. Sugar Beet Technol. 17:126-133.

Rudolph, G., R. Dahl, and J. Coffman. 1980. Deep soil sampling and the effect of nitrogen on quality sugarbeets. 1979 Sugarbeet Res. and Ext. Rep., North Dakota State Univ. Ext. Ser. 10:134-137. (www.sbreb.org)

Scarsbrook, C.E. 1965. Nitrogen availability. p.486-507. In W.V. Bartholomew and F.E. Clark (ed.). Soil Nitrogen. Am. Soc. Agron., Madison, WI.

Schmehl, W.R., R. Finkner, and J. Swink. 1963. Effect of nitrogen fertilization on yield and quality of sugar beets. J. Am. Soc. Sugar Beet Technol. 12:540-544.

Shock, C.C., M. Seddigh, L.D. Saunders, T.D. Stieber, and J.G. Miller. 2000. Sugarbeet nitrogen uptake and performance following heavily fertilized onion. Agron. J. 92:10-15.

Sims, A.L., J.T. Moraghan, and L.J. Smith. 2002. Spring wheat response to fertilizer nitrogen following a sugar beet crop varying in canopy color. Prec. Agric. 3:283-295.

Smith, L.J. 1996. Nitrogen status changes in a commercial field in a 4-year sugarbeet rotation a year after sugarbeet. p. 1995 Sugarbeet Res. and Ext. Rep., North Dakota State Univ. Ext. Ser. 26: 117-119. (www.sbreb.org)

Smith, L.J. 1997. Nitrogen status changes in a commercial field in a 3-year sugarbeet rotation- A 4-year summary. 1996 Sugarbeet Res. and Ext. Rep., North Dakota State Univ. Ext. Ser. 27: 88-91. (www.sbreb.org)

Soine, O.C. 1973. Sugarbeet research at northwest experiment station, Crookston, in 1972. 1972 Sugarbeet Res. and Ext. Rep., North Dakota State Univ. Ext. Ser. 3: 70-75. (www.sbreb.org)

Soper, R.J., and P.M. Huang. 1963. Effects of nitrate nitrogen in the soil profile on response of barley to fertilizer nitrogen. Can. J. Soil Sci. 43:350-358.

Stockinger, K.R., A.J. MacKenzie and E.E. Cary. 1963. Yield and quality of sugarbeets as affected by cropping systems. J. Amer. Soc. Sugar Beet Technol. 12:492-496.

Torkelson, R. 1972. Why guess-soil test. 1971 Sugarbeet Res. and Ext. Rep., North Dakota State Univ. Ext. Ser. 2: 32-30..(www.sbreb.org)

Winner, C. 1993. History of the crop. p.1-35. In D.A. Cooke and R.K. Scott (ed.), The Sugar Beet Crop. Chapman & Hall, NY.

Winter, S.R. 1984. Cropping systems to remove excess soil nitrate in advance of sugarbeet production. J. Amer. Soc. Sugar Beet Technol. 22:285-306.