Sugarbeet (Beta vulgaris L.) Response to Inorganic Fertilizer-Nitrogen in North Dakota and Minnesota During the Last 40 Years

A. Chatterjee[1], A.L. Sims[2], D. Franzen[1], A. Cattanach[3]

[1]*Department of Soil Science, North Dakota State University, Fargo, ND 58108*

[2]*Northwest Research and Outreach Center, University of Minnesota, Crookston, MN*

[3]*American Crystal Sugar Company, Moorhead, MN 56560*

Corresponding author:amitava.chatterjee@ndsu.edu

CORE IDEAS:

- Average sugarbeet yield has increased from 38.8 to 82.9 Mg ha^{-1} since 1971.
- Previous recommended nitrogen (N) rate of 146 kg N ha^{-1} did not consider current yield potential.
- Fertilizer-N response increased in Red River Valley (RRV) but declined in southern MN.
- Sugarbeet after corn requires 100 kg N ha^{-1} more than after spring wheat.
- Fall-N application requires an extra 16 kg N ha^{-1} compared to spring to optimize sugar yield.

Keywords: Recoverable sugar yield, previous crop, fertilizer application time

Abbreviations: RRV, Red River Valley; RSY, recoverable sugar yield; NUE, nitrogen use efficiency; SLM, sugar losses to molasses

ABSTRACT

The Red River Valley (RRV) of North Dakota and Minnesota, and Southern Minnesota is considered as the major sugarbeet (*Beta vulgaris* L.) production areas of the United States. Sugarbeet

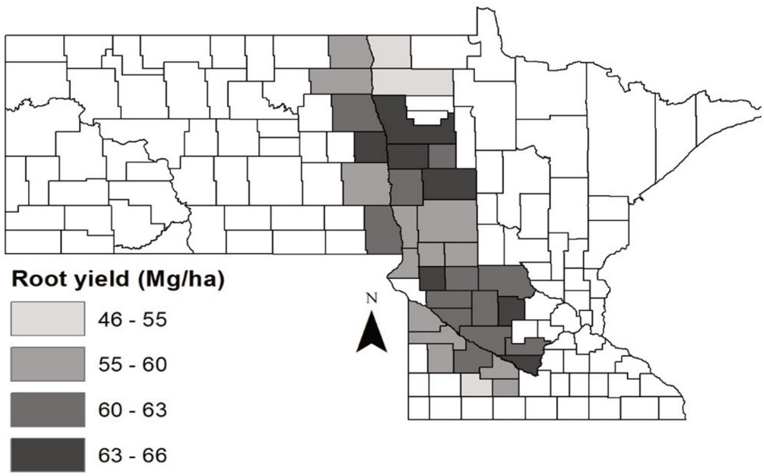
root yield and sugar content are subject to the soil nitrogen (N) supply. Current recommendations, established in 2001, suggests a single application rate of 146 kg N ha^{-1} irrespective of soil type and organic matter content. To improve the fertilizer-N use efficiency, it is critical to understand factors controlling sugarbeet response to fertilizer-N across this region. Fifty-six fertilizer-N response trials (number of observation= 971), conducted in the last 40 years, were analyzed to determine the variability in fertilizer-N rate to optimize recoverable sugar yield (RSY). Average sugarbeet root yield increased from 38.8 Mg ha^{-1} (in 1971) to 82.9 Mg ha^{-1} (in 2016). Considering trials conducted from 2000-2016, RSY was optimized at 142 kg fertilizer-N ha^{-1} to optimize RSY when both the RRV and Southern MN were combined; but separately, it was 159 kg N ha^{-1} for the RRV and 113 kg N ha^{-1} for Southern MN. Moreover to optimize RSY sugarbeet after corn (*Zea mays*) required an additional 100 kg N ha^{-1} compared to a previous crop of spring wheat (*Triticum aestivum*) and fall-N applications would need extra 16 kg N ha^{-1} compared to spring-N application. Consideration of profile soil nitrate-N, previous crop in rotation and fertilizer-N management practices can be used to improve current N recommendation.

INTRODUCTION

Sugarbeet production in North Dakota (ND) and Minnesota (MN) comprises over 50% of US production (USDA, NASS, 2016). Nitrogen (N) nutrition of sugarbeet is closely associated with root yield, sucrose- and purity-percentage (Carter et al. 1976, Gehl and Boring 2011). A steady soil N supply promotes vigorous early season vegetative growth, and canopy closure, which allows sugarbeet to use solar energy efficiently to increase both yield and quality (Lamb et al., 2001). An inadequate supply of fertilizer-N below the plant's demand can result in significant yield reduction, while excess fertilizer-N may lead to decreased sugar content and increased impurities (Tarkalson, 2011; Franzen 2003; Lamb et al., 2001). An inverse relationship between root yield (tonnage) and sucrose concentration has posed a challenge for sugarbeet agronomist in determining the targeted N rate to optimize recoverable sugar yield (RSY) (Campbell, 2002).

The current N recommendation for sugarbeet production across ND and MN is based on a yield goal of 45 Mg ha^{-1}. It has been recommended to apply a single N application rate of 146 kg N ha^{-1} as a total of fertilizer-N and soil available nitrate-N (NO_3-N) within a 120 cm soil depth (Lamb et al. 2001). Setting the target N availability level at 146 kg N ha^{-1} was derived as the most economical rate of available N based on field research trial data from the Northwest Research and Outreach Center (Crookston, MN) and the Southern Minnesota Beet Sugar Cooperative (Renville, MN) combined with various payment structures of three sugarbeet cooperatives (Sims 2011). Sugarbeet root yields have substantially increased over time with the introduction of Rhizomania resistance and glyphosate-resistant cultivars (Khan 2010, Morishita 2018). Weed-free field condition have also improved root yield and N-use efficiency (Sims 2011; Tarkalson, 2011). In 2016, average root yield varied significantly from 47 to 80 Mg ha^{-1} across 24 counties of MN and 7 counties of ND (Fig.1) (USDA, NASS, 2016; personal communication

Figure 1. Distribution of average sugarbeet root yield (Mg ha^{-1}) across 24 counties of MN and 7 counties of ND during 2016 growing season.



with Tyler Grove and Mike Metzger, agronomists of American Crystal and Minn-Dak Farmers Cooperative, respectively). Campbell (1995) reported that the county mean yields were highest (average=40.4 Mg ha^{-1}) in the Southern MN counties (Chippewa, Kandiyohi) and lowest (average= 35.4 Mg ha^{-1}) in the Northern Red River Valley (RRV). Sugarbeet response to fertilizer-N also depends upon residual soil NO_3 concentrations in the upper 120 cm of soil prior to planting (Carter et al. 1974, Giles et al. 1975, Moraghan et al. 2003), previous crop (Larney et al. 2016, Overstreet et al. 2008, Sims 2008) and N application timing (Carter 1984, Moraghan 2004).

Determination of available residual N is critical, particularly to counteract the detrimental effects of excessive deep residual N (Carter et al. 1974; Campbell, 2002). Sugarbeets can acquire N down to a soil depth of at least 2.5-3.0 m (Stevanato et al. 2010). Bilbao et al. (2004) reported that knowledge of soil NO_3-N before planting is a useful method for assessing the N fertilizer rate for sugarbeet production. Combining yield goals and soil test NO_3-N have assisted farmers in determining pre-plant/or in-season fertilizer N rate. Inclusion of yield goals has the potential risk of predicting growing season environment (good or bad year), but sugarbeet growers used it due to the lack of improved options (Raun et al. 2017). The concept of a yield goal has failed to predict current-year yields due to the unpredictable influence of environment (Raun et al. 2017). Current fertilizer-N requirements may increase because of increased annualized production, reduced contribution of N mineralization and increased immobilization and volatilization potential of surface-applied fertilizer-N (Schlegel et al. 2005). Hergert (2010) reported quite different N recommendation systems from region to region, reflecting a good degree of site specificity that is important for improved N use efficiency and lower environmental effects. In Nebraska, Anderson and Peterson (1988) found optimum N rates were 50 kg ha^{-1} higher for root yields than for maximum sucrose production.

In Idaho, Carter and Traveller (1981) concluded that, N fertilizer should be applied before planting or during the early plant growth stages at amounts needed for optimum plant growth and sucrose production that are based on reliable soil tests for maximum return. Cater (1984) concluded similar N use efficiency of sugarbeet in response to fall and spring applied fertilizer N. Moraghan (2004) found negligible loss (2-5%) of fall applied urea under sugarbeet production. Recommended fertilizer rates are subject to potential error due to N mineralization and immobilization associated with residue decomposition (Moraghan et al. 2003). Koch et al. (2018) found that sugar yield was 5% higher after pea (*Pisum sativum* L.) compared to maize (*Zea mays* L.). Sims (2008) documented that growing sugarbeet after a wheat crop is consistently the better rotation of corn, soybean (*Glycine max*) and hard red spring wheat and the negative effect of growing sugarbeet after soybean were not great as growing sugarbeet after corn.

Since 1971, the Sugarbeet Research and Education Board of ND and MN annually publishes research outcomes from trials conducted on various aspects of sugarbeet production. This manuscript is an endeavor to summarize the last 40-years of sugarbeet response to fertilizer-N application rate trials from these studies. It was hypothesized that introduction of new cultivars resistant to Rhizomania and glyphosate has improved the N use efficiency (NUE) with a subsequent reduction in fertilizer-N demand. Fertilizer-N rate to optimize RSY was calculated using the quadratic fit of recoverable sugar yield and fertilizer-N application rate before and after 2000. Moreover, variation in N response between the RRV and Southern MN was examined. Variability of initial soil nitrate (NO_3)-N, fertilizer-N application timing (Fall vs. Spring) and previous crop in rotation were also evaluated.

METHODS

Data collection:

Data were collected from annual Sugarbeet Research and Education reports from 1971-2016 (http://www.sbreb.org/research/research.htm) on research trials targeting sugarbeet yield response to fertilizer N application rates (Appendix Table 1). For each study, information was collected on growing year, field location, fertilizer-N application timing, fertilizer-N application rate, root yield, sugar percent, sugar yield, initial soil nitrate-N to a 120 cm soil depth, previous crop and soil organic matter content. Studies consisted a minimum of a control (check) and at least one fertilizer-N application rate. Only N supplied as fertilizer was considered and other factors including cultivar, plant population, nitrogen response to yield and sugar values for each treatment factor were used for this study. Various types of inorganic N fertilizers were included in this summary with the exception of enhanced efficiency fertilizer products such as ESN or the addition of inhibitors. The final dataset consisted of 971 observations of sugarbeet root yield, but only 783 observations of sugar % and 940 observations of RSY to fertilizer N application rates. Nitrogen use efficiency is calculated by dividing the recoverable sugar yield (kg ha^{-1}) with applied fertilizer-N (kg ha^{-1}). In the absence of tables, data were extracted from figures using WebPlotDigitizer version 4.1 (https://automeris.io/WebPlotDigitizer).

For field experiments, the middle two rows of the plot were mechanically harvested. Plot size is generally 9 m by 1.4 m with 0.6 m row spacing. A subsample of 15-20 roots were placed in a rubber harvest bag and along with the experimental unit identifying tag sent to the American Crystal Sugar Quality Tare Lab East Grand Forks, MN for quality analysis the same date as harvest. Sucrose concentration, alpha amino-N, sodium and potassium concentrations were analyzed. Sugar loss to molasses was calculated using a modified Carruther's equation (Carruther, 1961).

Data treatment and statistical analyses

Percent relative RSY, sugar percent and RSY for each observation were calculated by dividing each observation with the highest respective response of each individual trial (Asghari and Hanson, 1984). In the case of multiple location studies, maximum response for each site was utilized for analysis. Quadratic fit of changes in percent relative yield, sugar percent and RSY with fertilizer N application rate were performed using SAS 9.4 (SAS Institute, Cary, NC) at 95% significance level. The quadratic model was fit to yield and quality parameters for fertilizer-N application rates with the REG procedure of SAS. The quadratic model is defined by

$$Y = aN^2 + bN + c$$

Where Y is the yield parameter and N is the rate of N applied as fertilizer (kg N ha^{-1}). The coefficients a, b, and C are the intercept, linear and quadratic coefficients, respectively. Optimal rates of N fertilizer for yield, sugar and RSY were determined by setting the first derivative of the quadratic model equal to zero and solving for N rate.

$$N_{max} = -b/2a$$

Influence of initial soil nitrate-N, previous crop and soil organic matter content (as independent variables) on RSY (dependent variable) were also analyzed using quadratic equation. Finally, observations were separated into Southern Minnesota and the RRV to determine whether fertilizer-N response varied between these two regions. Quadratic equations were solved to determine the optimum N rate, when changes in maximum relative RSY with fertilizer-N application rate is equal to one.

RESULTS AND DISCUSSION

Changes in root yield and sugar content over the last 40 years are presented in Fig. 2. Average root yield increased from 38.8 Mg ha^{-1} (in 1971) to 82.9 Mg ha^{-1} (in 2016), an increase of nearly 1.0 Mg ha^{-1} yr^{-1}. Moreover, a significant increase in yield was observed since 2000 as indicated by a shift in the trendline, just after the release of current recommendation. An increase in sugarbeet root yield was continuous even before 1970. Campbell (1995) reported average rate of 0.5 Mg ha^{-1} yr^{-1} during 1950's-1970's. National average beet yield increased 0.36 Mg ha^{-1} yr^{-1} during 1909-2010, an approximately 1 Mg ha^{-1} increase every three years (Tarkalson, 2012). However, the sugar content did not change over time with an average sugar content of 16.2±2.0 percent. Average RSY increased from 6,665 kg ha^{-1} (in 1971) to 14,326 kg ha^{-1} (in 2016), due to the increase in root yield. Average fertilizer-N use efficiency increased from 61 to 114 kg recoverable sugar/kg fertilizer-N during the period 1971 to 2016.

Changes in relative root yield, sugar percent and RSY with fertilizer-N rates were presented in Fig. 3. According to quadratic fit, the greatest relative root yield was achieved with 249 kg N ha^{-1} and highest relative recoverable sugar content was achieved with 167 kg N ha^{-1}, but addition of any amount of fertilizer-N only reduced the sugar content. Similarly, Sims (2011) concluded that sugarbeet root yields increased up to 270 kg N ha^{-1} but sugar content was optimized at 100 kg N ha^{-1} in the Northern RRV. In Nebraska, Anderson and Peterson (1988) determined optimum N rate was 50 kg ha^{-1} higher for root yield than for maximum sugar production. Under excess soil available N, sugar recovery is reduced due to decrease in the proportion of root biomass and increase in concentration of soluble nitrogenous compounds (Draycott and Christenson, 2003).

RSY integrates both root yield and sugar content and is the basis for grower payment (Franzen, 2003); thus influence of N rate on RSY will be further explored. Data were separated out into two-time periods, before (1971-1999) and after (2000-2016) of the release of current

Figure 2. Changes in (a) sugarbeet root yield (Mg ha-1), (b) sugar content (%), (c) recoverable sugar yield (kg ha-1), and (d) nitrogen use efficiency (kg recoverable sugar/kg fertilizer N) in the Red River Valley of ND and MN and southern MN during 1971-2016. (n= number of observations and red dotted line indicated the linear trend over time)

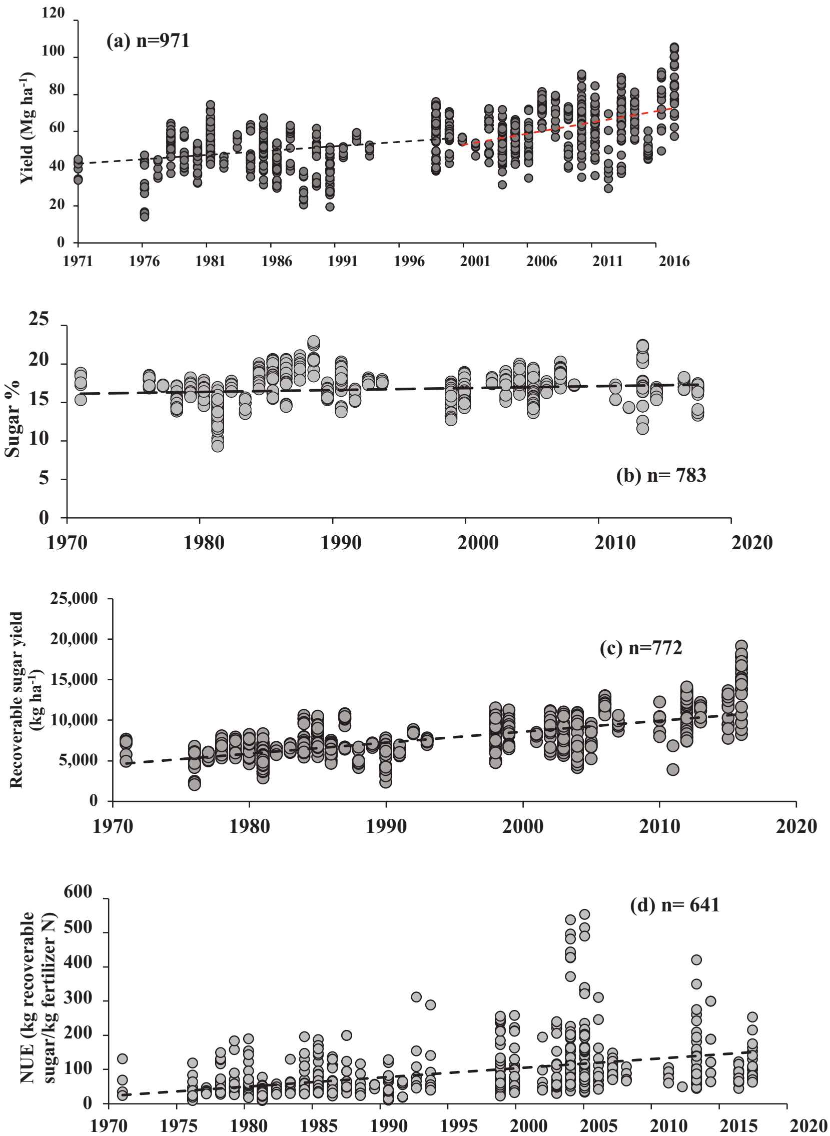


Figure 3. Quadratic fit between percent maximum relative- (a) root yield, (b) sugar and (c) recoverable sugar yield and fertilizer N application rates for studies conducted in RRV of ND and MN, and southern MN during 1971-2016. Red dotted line indicates 95% confidence interval of the fit.

Figure 3 (a)

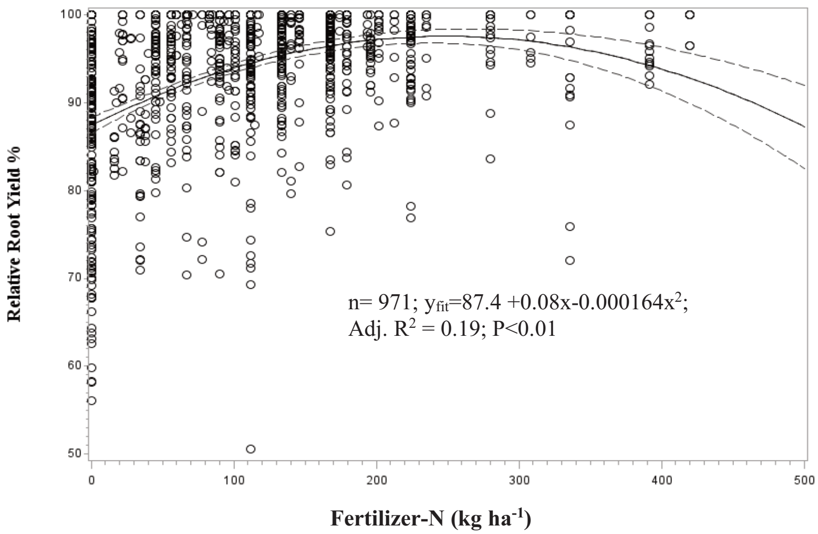


Figure 3 (b)

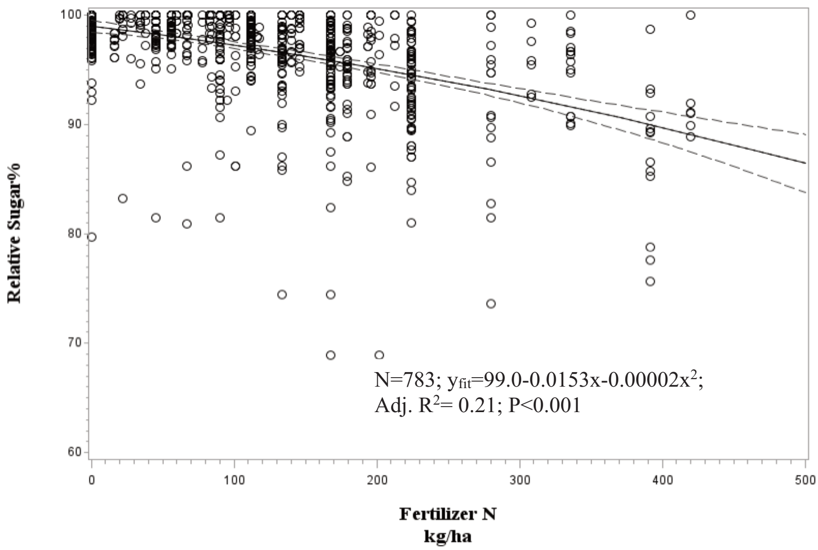
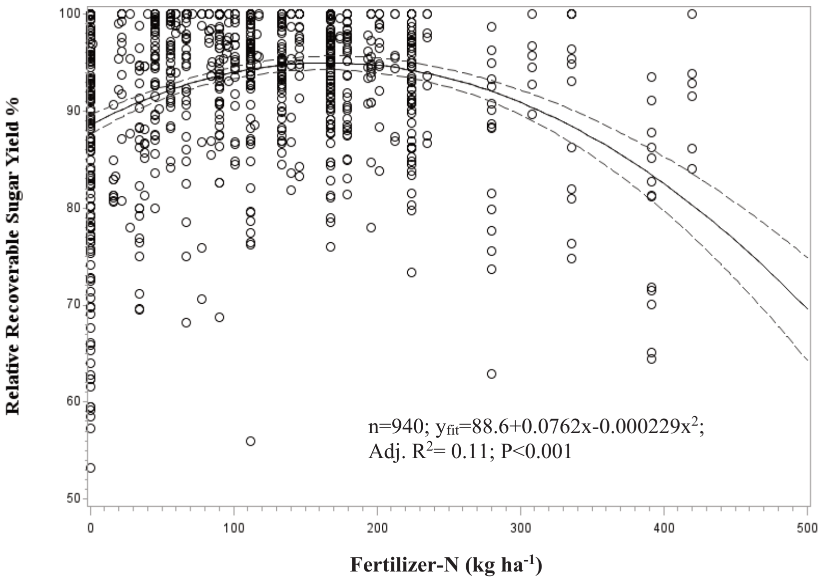


Figure 3 (c)

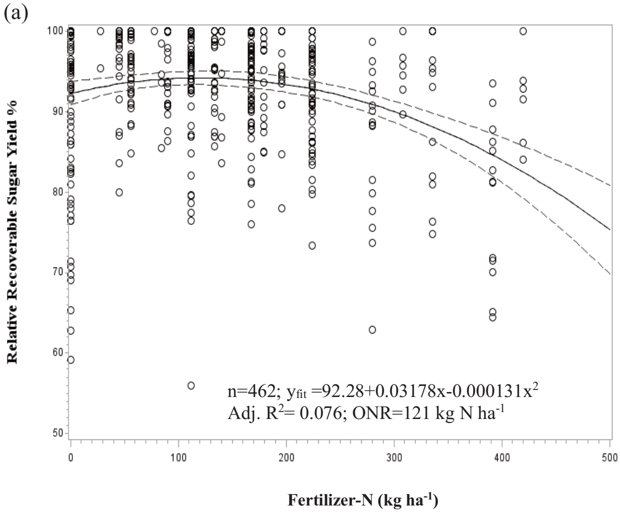


fertilizer recommendations to find out whether there is a shift in fertilizer-N response since 2000. Changes in RSY with fertilizer N rates before and after 2000 were presented in Fig. 4(a) and (b), respectively. Before 2000, RSY was optimized with 121 kg N ha^{-1} but with 142 kg N ha^{-1} for data from 2000-2016. Average root yield was increased 0.5 Mg ha^{-1} yr^{-1} during 1970 to 2000, but it was improved to 1.8 Mg ha^{-1} yr^{-1} during 2000 to 2016 (Fig. 2a). Increase in sugarbeet N demand over time might be due to increased root yield contributed by significant improvement in cultivar and soil and crop management practices.

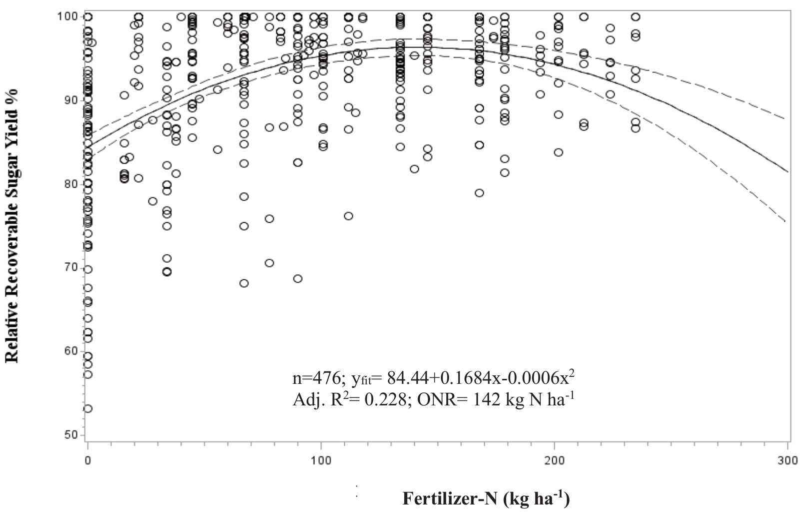
Current sugarbeet recommendation did not consider the differences in production potential between the RRV and Southern MN (Fig. 1). The optimum N response was distinctly different between these two regions (Fig. 5). In the RRV, optimum RSY was achieved with 69 kg N ha^{-1} during 1970-1999 (Fig. 5a), but increased to 159 kg N ha^{-1} during 2000-2016 (Fig. 5b). Since 2002, a significant shift in crop rotation from highly diversified small grain dominated crops (i.e., wheat, barley) to intensive corn-soybean based rotation occurred in the RRV (Aguilar et al. 2015). Sugarbeet production was significantly influenced by preceding crop that was grown, as observed by Sims (2008), Lamb et al. (2009), and Overstreet et al. (2009). Consensus was that root yield was greater following wheat than corn irrespective of fertilizer-N application rate. After soybean, yield was better than after corn but still less than following wheat (Sims 2008).

Figure 4. Quadratic fit between relative recoverable sugar yield (%) and fertilizer-N and optimum N rate (ONR) from fit during (a) 1970-1999 and (b) 2000-2016 in in the Red River Valley of ND and MN and southern MN. (n= number of observations and red dotted line indicated the linear trend over time)

Figure 4 (a)



4 (b)



In southern MN, fertilizer-N rate to optimize RSY declined from 132 kg N ha^{-1} (Fig. 5c) to 113 kg N ha^{-1} (Fig. 5d) over time. Minnesota ranks third in the United States in swine (*Sus scrofa*) production and the field application of swine manure is common practice in this growing region (Vetsch et al. 2017). Since 2000, as the size of confined swine production facilities has increased but cropland area receiving manure has not been increased (Schmidt et al. 2001). Continuous application of manure might have reduced the fertilizer-N response of sugarbeet in Southern MN.

Control of initial soil nitrate-N, previous crop and soil organic matter content on relative RSY was presented in Fig. 6. Maximum RSY was achieved with initial soil NO_3 content of 259 kg N ha^{-1} (Fig 6a). Jaggard et al. (2009) reported beet grown in peat soil or recent large amount (>150 kg N ha^{-1}) organic manure addition never responded to any applied fertilizer N. Fertilizer-N application timing also has a significant influence on RSY. Highest relative RSY was achieved with fertilizer-N application of 141 kg N ha^{-1} for fall (Fig 6b) and 125 kg N ha^{-1} for spring (Fig 6c) applied fertilizer-N. Recovery of N^{15}-labeled, fall applied urea-N by wheat was less than with spring applied urea-N when fall and spring precipitation was above normal (Cattanach, 1981). Randall and Vetsch (2005) determined the six-year average relative efficiency of N, applied as anhydrous ammonia, was 79% for fall and 95% for the spring pre-plant with annual variation of 22 to 113% for fall and 78 to 110 for spring, under corn production in MN.

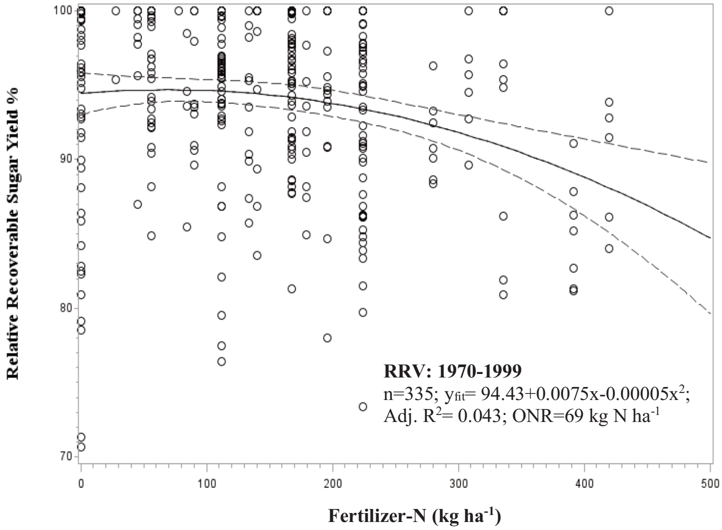
Sugarbeet is mostly planted after spring wheat in the northern RRV and after corn and soybean in the Southern- RRV and MN (Wiersma et al. 2010). After corn, the highest RSY was achieved with 216 kg fertilizer-N ha^{-1} (Fig 6d), but the same was achieved with 116 kg N ha^{-1} after spring wheat (Fig 6e). The negative effect of sugarbeet following corn was reported by several researchers (Sims 2008; Overstreet et al. 2009). Sims (2008) concluded growing sugarbeet after a wheat crop was consistently the better rotation than following corn or soybean and root yields were greater following wheat than corn irrespective of fertilizer-N. Christenson and Butt (2000) also determined that approximately 100 kg N ha^{-1} more was required to reach optimum beet yield or RSY following corn as compared to following field bean and the difference in yield could not be explained by soil N or carry-over soil moisture. In Germany, Koch et al. (2018) recorded 5% higher sugarbeet yield after pea compared to corn and decreased sugarbeet growth after corn that could not be compensated completely by high fertilizer-N rate.

Fertilizer-N use by sugarbeet growers has a clear geospatial relationship. Campbell (1995) reported counties in southern part had higher variability and higher average yield than northern counties due to a longer growing season. In the northern RRV, Sims (2014) observed there are several areas (stretched out from Polk county to Marshall and Kittson counties in MN) with higher N application rate than current N recommendation; these areas have lower root yield but higher quality

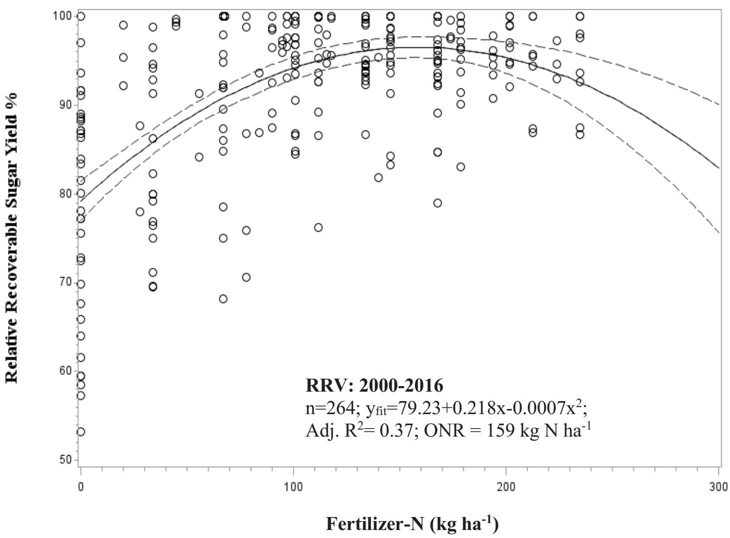
Figure 5. Quadratic fit between relative recoverable sugar yield (%) and fertilizer-N and optimum N rate (ONR) from fit during (a) 1970-1999 and (b) 2000-2016 in the Red River Valley of ND and MN and (c)1970 and (d) 2000-2016 in the southern MN. (n= number of observations and red dotted line indicated the linear trend over time)

Figure 5

(a)



(b)



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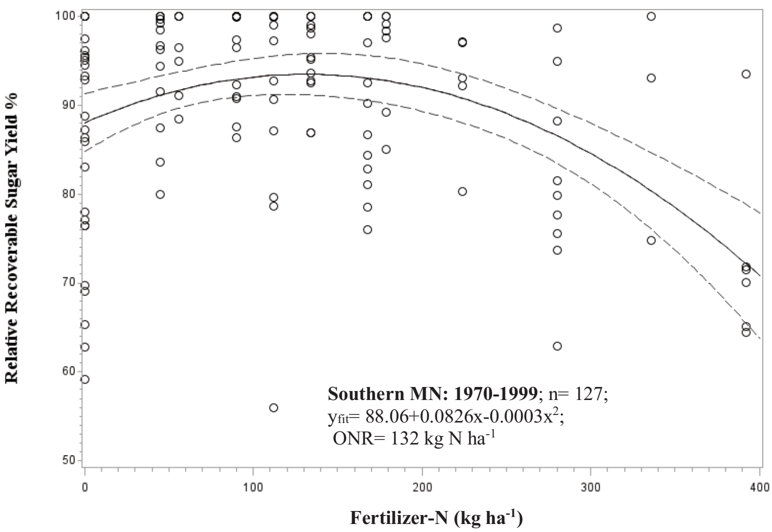

Relative Recoverable Sugar Yield %
Fertilizer-N (kg ha-1)
Southern MN: 1970-1999; n= 127;
yfit= 88.06+0.0826x-0.0003x2;
ONR= 132 kg N ha-1

(d)

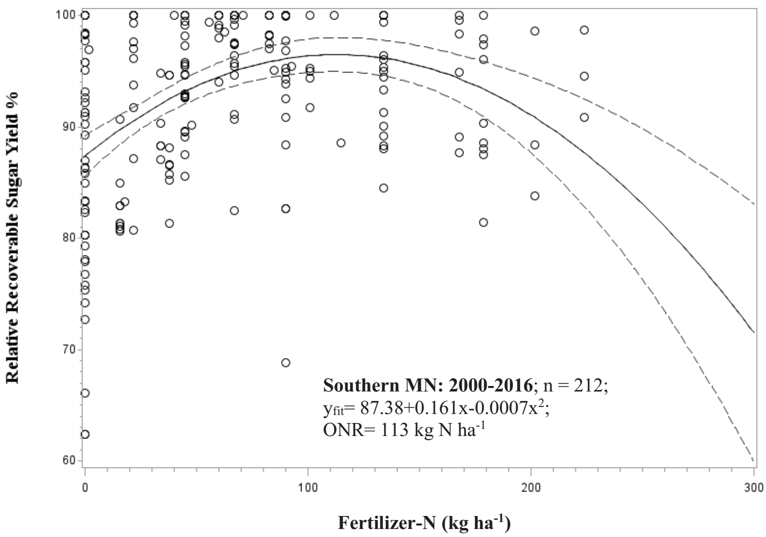

Relative Recoverable Sugar Yield %
Fertilizer-N (kg ha-1)
Southern MN: 2000-2016; n = 212;
yfit= 87.38+0.161x-0.0007x2;
ONR= 113 kg N ha-1

Figure 6. Quadratic fit between relative recoverable sugar yield and (a) initial soil nitrate-N, (b) fall applied- and (c) spring-applied N, previous crop- (d) corn and (e) spring wheat content, for studies conducted in RRV of ND and MN, and southern MN during 1971-2016. Red dotted line indicates 95% confidence interval of the fit.

Figure 6 (a)

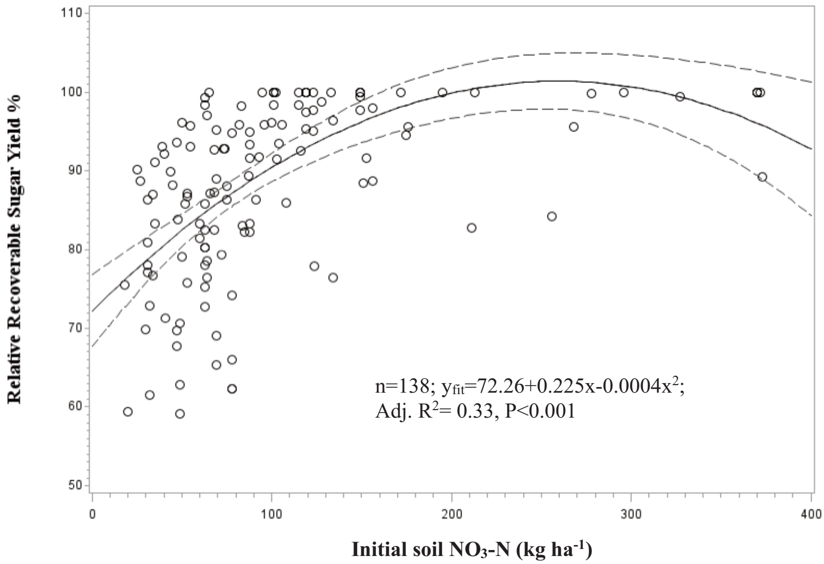


Figure 6 (b)

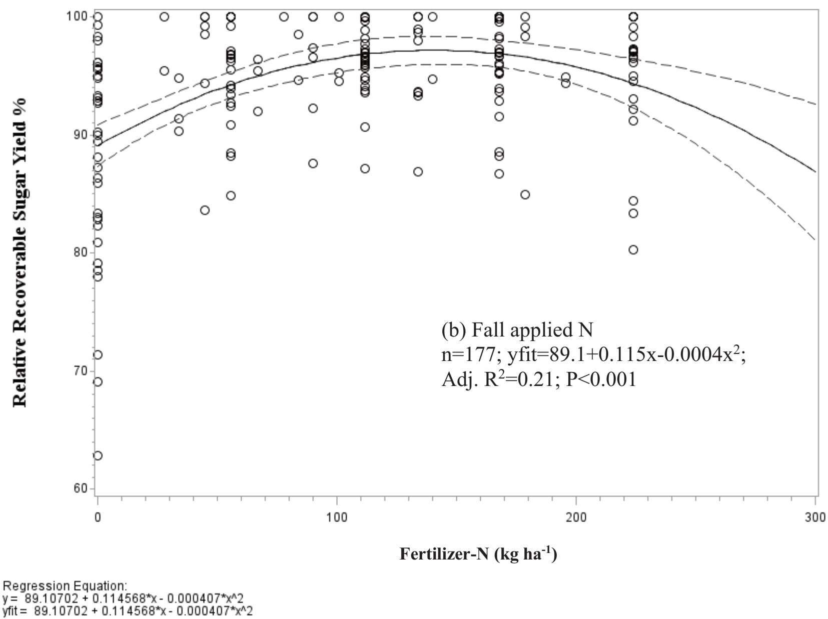


Figure 6 (c)

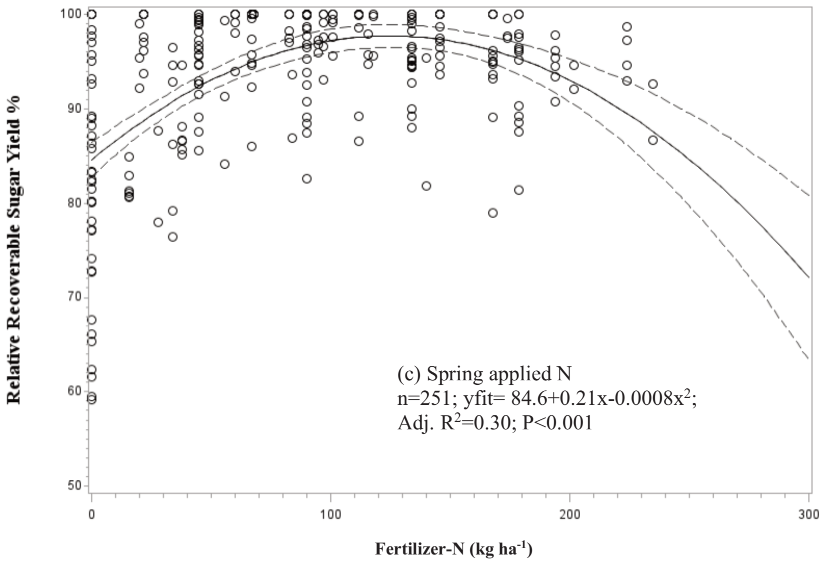


Figure 6 (d)

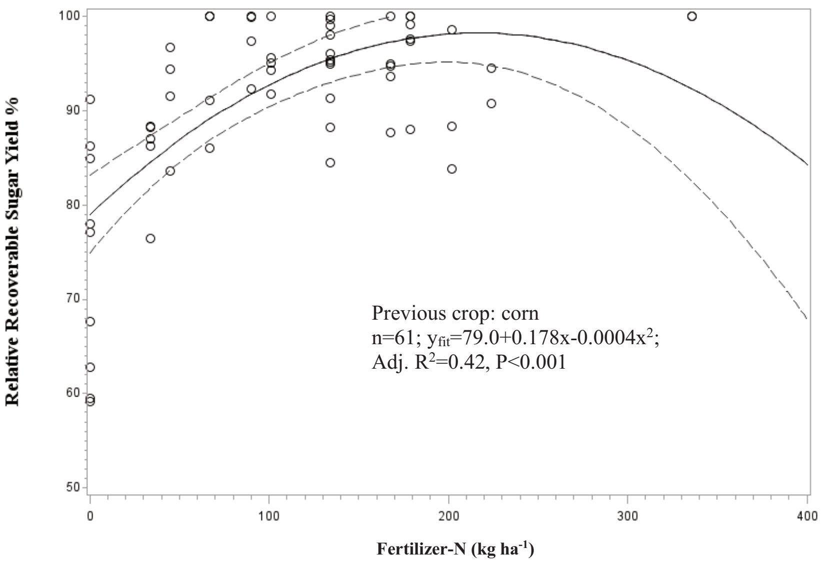
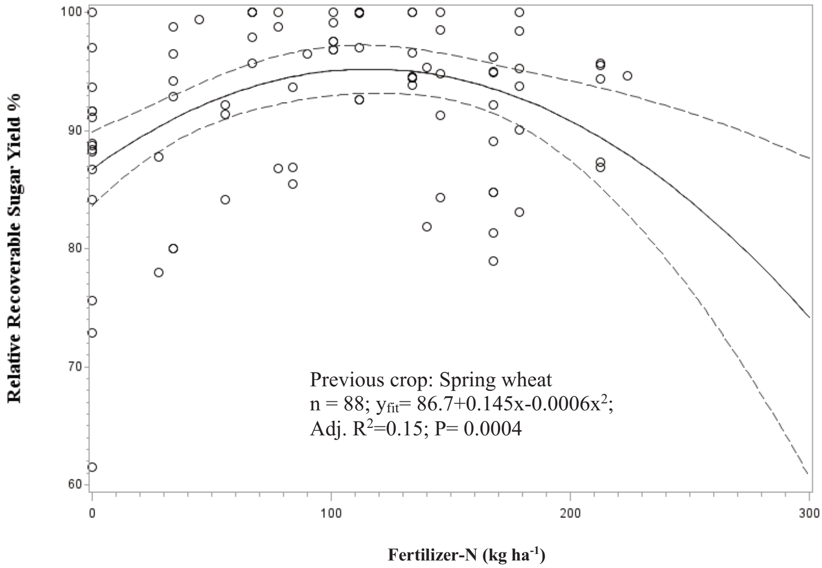


Figure 6 (e)



than rest of the RRV and Southern MN. In Southern MN, Lamb et al. (2014) noted a reduction in fertilizer-N recommendation by 56 kg N ha^{-1} since 2002 thereby providing increased quality without sacrificing yield. Significant mineralization of N from high soil organic matter content in the southern MN significantly reduce the fertilizer-N demand than northern area.

CONCLUSIONS

Sugarbeet response to fertilizer-N has significantly changed over time across this region. A single fertilizer-N application rate might not be suitable to optimize the RSY and N use efficiency for the entire region. More on-farm research data is needed to understand the control of preceding crop in rotation and N application timing, and soil available N on RSY. Development of future N recommendation program should consider soil organic matter variability, previous crop and application timing to reduce N losses and to increase N use efficiency of sugarbeet production system in this region.

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