Improving Nitrogen Management in Pacific Northwest Sugarbeet Production

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ABSTRACT

Nitrogen (N) management is critical in sugarbeet production to optimize yield and quality. Although, past research has been critical to improving and understanding sugarbeet N nutrition, continued research is needed to evaluate evolving varieties and management practices. From 2005 to 2010, studies from 14 locations (14 site-years) were conducted by agronomists from The Amalgamated Sugar Company (TASCO) and scientists at the USDA-ARS Northwest Irrigation and Soils Research Laboratory to evaluate the effect of N supply (fertilizer N + spring soil residual N [Nitrate N (NO_3-N) + Ammonium N (NH_4-N)]) on sugarbeet production in the Pacific Northwest. At each site-year, the effect of various levels of N supply on estimated recoverable sucrose (ERS) yield, root yield, sucrose concentration, brei nitrate concentration, and nitrogen use efficiency (NUE) were assessed. Nitrogen supply significantly affected ERS yield for 6 of the 14 site-years. For the 8 non-responsive sites, the maximum ERS yield was assumed to be the lowest N supply. The average nitrogen requirement (Nr) at maximum ERS yield across all site-years was 2.25 kg N Mg^{-1} beet and ranged from 1.4 to 3.7 kg N Mg^{-1} beet. Thirteen of the 14 site-years had an Nr at or below 2.8 kg N Mg^{-1} beet, substantially less than current recommendations of 3.5 to 4.0 kg N Mg^{-1} beet. Nitrogen requirements can be reduced in the Pacific Northwest sugarbeet production area compared to past recommendations resulting in reduced N fertilizer applications and significant cost savings.

Additional Key Words: nitrogen, nitrogen use efficiency, nitrogen requirement.

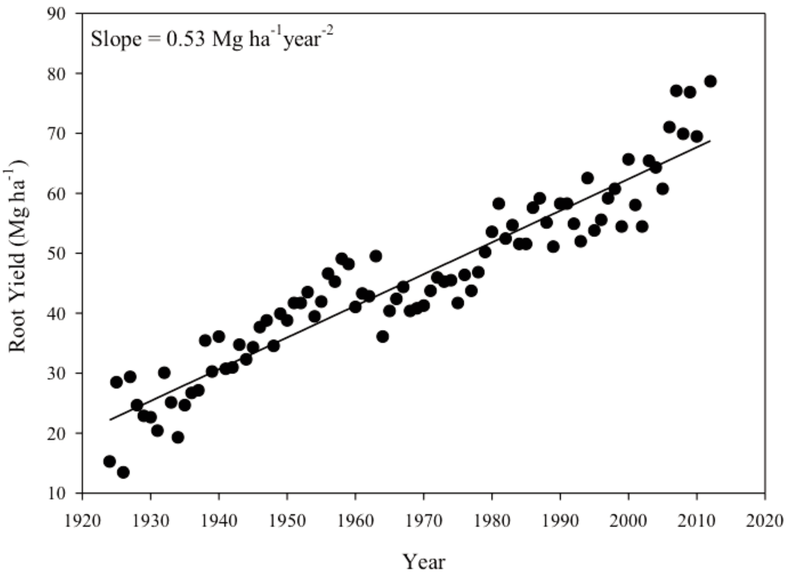
Abbreviations: ERS = estimated recoverable sucrose, NUE = nitrogen use efficiency, UAN = urea ammonium nitrate, Nr = nitrogen requirement, RY = root yield

The sugarbeet production in the Pacific Northwest is located primarily from south central Idaho to southeastern Oregon. Beets are produced by growers who are part of The Amalgamated Sugar Company (TASCO), a grower-owned cooperative. From 2000 to 2010 an average of 76,000 ha year^{-1} of sugarbeets were harvested in this growing area (National Agricultural Statistics Service, 2015).

Proper nitrogen (N) management is critical to sugarbeet production due to decreased profits associated with both under- and oversupply relative to crop requirements (Stout, 1960). Under supplying N reduces root and sucrose yields while over supplying N results in decreased sucrose content and increased root impurities further reducing sucrose extraction (Carter and Traveller, 1981; James et al. 1971). Compared to other crops, sugarbeets require a relatively narrow range of N supply to optimize yield, quality and economic return. Many research studies have been conducted to evaluate N management in sugarbeet production across the U.S. (Adams et al., 1983; Anderson and Petersen, 1988; Carter et al., 1974 and 1976; Halvorson and Hartman, 1975 and 1980; Halvorson et al., 1978; Hills and Ulrich, 1976; Hills et al., 1978 and 1983; Lamb and Moraghan, 1993; Stark et al., 1997; and Stevens et al., 2007). In Idaho, the Cooperative Fertilizer Evaluation Program (CFEP) was conducted from 1993 to 1997 to update fertilizer recommendations for sugarbeets using 37 on-farm trials (Stark et al., 1997). The most current version of University of Idaho sugarbeet N fertilizer recommendations are the same as the 1997 recommendations (Moore et al., 2009). All of these studies, excluding Stevens et al. (2007), were conducted 17 to 35 years ago. Nitrogen management recommendations can change as yields and crop production efficiencies increase over time, resulting in the need for continued evaluation of sugarbeet response to N (Dobermann et al., 2011). Idaho sugarbeet yields have increased by an average of 0.53 Mg ha^{-1} year^{-1} from 1924 to 2012 (Figure 1) while general N fertilizer requirements for sugarbeet production in the TASCO growing area have ranged from 0 - 11.8 kg Mg^{-1} applied or total N between 1898 to 2009 (Table 1).

In the U.S. sugarbeet industry, one measure of N requirement (Nr) or efficiency for sugarbeet production is the kg of N needed (fertilizer N + residual soil inorganic N [nitrate-nitrogen (NO_3-N) and ammonium-nitrogen (NH_4-N)]) to produce one Mg of sugarbeets (Hills and Ulrich, 1976). In the TASCO growing area, the quantity of N fertilizer

Figure 1. Average sugarbeet yield over time in Idaho.



recommended is determined from residual soil inorganic N concentration obtained from soil samples (from 0 to 0.61 or 0.91m depths) and field specific yield goals. However, the total N available to crops includes N from in-season mineralization of soil organic matter (Westermann and Carter, 1975). Due to difficulty in predicting amounts of N derived from in-season mineralization, most recommendations do not directly account for the derived N, but indirectly account for it by correlating nitrogen supply with yield. The variation in N mineralization across space and time is likely a major cause for variations in calculated optimum Nr values thus highlighting a gap in knowledge to further improve N management in sugarbeet production. Without accurate predictions of in-season N mineralization across space and time, fine-tuning the amount of N added in fertilizer and residual soil inorganic N available at the start of the season is the next most logical approach.

The most recent University of Idaho sugarbeet N recommendations have an Nr range of 3.6 to 7.5 kg N Mg $^{-1}$ beets over a yield goal range of 49 to 109 Mg beets ha^{-1} (Table 1, Moore et al, 2009). The recommendations state that the table values were to serve only as a general guideline and may vary based on site-specific factors. At average regional yield levels, the Amalgamated Sugar Company N recommendations prior to 2009 were aligned closely with the University of Idaho guidelines, with an added recommendation that growers not

Table 1. Selected history of N fertilizer recommendations in Idaho.

Year	Source	Nr (kg N Mg^{-1}; applied or total[†])	Comments
1898	C.W. McCurdy	0 – 2, applied	N fertilizer application not recommended for most situations. Manure application recommended if available. Recommended N fertilizer source was a 4% N 6.5% P_2O_5 and 10% K_2O source.
1931	S.B. Nuckols	0, applied	Soils supply sufficient N to meet needs. Recommendations for fertilizer N not fully developed.
1977	TASCO[‡]	3.7 – 8.0 total	Fertilizer recommendations derived from a table with adjustments based on a yield goal and soil inorganic N to a depth of 0.61 m. Nr increased as soil inorganic N concentration increased.
1984	University of Idaho[§]	1.8 – 11.8 total	Fertilizer recommendations derived from a table with adjustments based on a yield goal and soil inorganic N to a depth of 0.61 m. Nr increased as yield goal increased and soil inorganic N concentration increased.
1997	University of Idaho[¶] TASCO[‡]	3.6 – 7.5 total	Fertilizer recommendations derived from a table with adjustments based on a yield goal and soil inorganic N to a depth of 0.61 m. Nr increased as soil inorganic N concentration increased.
2009	University of Idaho[#]	3.6 – 7.5 total	Fertilizer recommendations derived from a table with adjustments based on a yield goal and soil inorganic N to a depth of 0.61 m. Nr increased as soil inorganic N concentration increased.
2009	TASCO[‡]	<4.0 total	Fertilizer Recommendations based on a site-by-site basis. Growers encouraged to use a historical yield goal based on field data, soil inorganic N to a depth of 0.91 m, and effects of past N management on beet sugar and brei nitrate concentrations to fine-tune fertilizer N rate.

[†] applied = N from fertilizer; total = applied + residual soil inorganic N (NO_3-N + NH_4-N).
[‡] The Amalgamated Sugar Company, 1977, 1997, 2009.
[§] Gallian et al., 1984. [¶] Stark et al., 1997. [#] Moore et al., 2009.

apply more than 4 kg N Mg^{-1} beets (TASCO, 2008). From 2009 to the present, TASCO has adjusted the N recommendations based on preliminary data analysis from some of the studies that will be presented in this paper (TASCO, 2009). The updated TASCO N recommendations use a more site-specific data step approach where Nr is adjusted based on past root brei nitrate level, sugar content, and N supply. The updated TASCO recommendation states that the Nr should not exceed 4 kg N Mg^{-1} beets and most production can be optimized below this Nr (TASCO, 2015). Although data from many of the studies presented in the paper have been used to justify changes to the TASCO N recommendations, there has not been a comprehensive evaluation and meta-based analysis of all the studies combined.

The objectives of this study were to evaluate the N response of sugarbeet grown across the TASCO growing area and determine if N recommendation adjustments are needed by comparing the results to past recommendations. The data set included in this paper constitutes the most recent research to better manage N in sugarbeet production in the Pacific Northwest.

MATERIALS AND METHODS

Site Descriptions

The data presented in this paper were from 14 research sites collected between 2005 and 2010 (Table 2). The sites covered the sugarbeet production area in southern Idaho, ranging from Cassia County in the east to Ada County in the west. Sites varied in soil type, general cultural practices (e.g. tillage, N fertilizer source, irrigation system, planting date, harvest date, variety planted) and research site set-up (e.g. plot size, N fertilizer rates, N fertilizer source and N fertilizer application rate) (Table 2 and Table 3). Planting dates ranged from late-March through April and harvest dates ranged from late-September to mid-October. Twelve of the research sites were located on grower production fields and two were located on the USDA-ARS research farm in Kimberly, ID. The sites located on the grower fields followed the production and cultural practices of the grower. However, there were some similar practices at each of the research sites.

- The previous crop at each site was barley or wheat.
- The experimental design was a randomized block with 4 to 8 replications.
- Plant stands were uniform and within the optimum plant densities based on TASCO recommendations.
- Between row spacing was 0.56 m.
- Irrigation timing and amounts scheduled to meet plant requirements.
- All sites had good weed control.
- Harvest area represented the center 2-rows and a length of 8.2 to 12.2 m row^{-1}.

Table 2. Site-year information.

Site	Year	City, County	Soil Texture	Plot Size	Tillage	Irrigation System
1	2005	Jerome, Jerome	sandy loam	2.2m × 10.7m	conventional	wheel line
2	2006	Jerome, Jerome	sandy loam	2.2m × 10.7m	conventional	wheel line
3	2006	Minidoka, Minidoka	sandy loam	2.2m × 10.7m	conventional	wheel line
4	2008	Kimberly, Twin Falls	silt loam	4.5m × 12.5m	strip, conventional	solid set sprinkler
5	2008	Acequia, Minidoka	silt loam	3.4m × 12.2m	conventional	hand line
6	2008	Glenns Ferry, Elmore	silt loam	3.4m × 12.2m	conventional	pivot
7	2009	Heyburn, Minidoka	sandy loam	3.4m × 12.2m	strip	wheel line
8	2009	Heyburn, Minidoka	sandy loam	3.4m × 12.2m	strip	wheel line
9	2009	Glenns Ferry, Elmore	silt loam	3.4m × 12.2m	conventional	pivot
10	2010	Jerome, Jerome	sandy loam	3.4m × 12.2m	conventional	pivot
11	2010	Burley, Cassia	clay loam	3.4m × 12.2m	conventional	pivot
12	2010	Glenns Ferry, Elmore	silt loam	3.4m × 12.2m	conventional	pivot
13	2010	Kuna, Ada	clay loam	3.4m × 12.2m	conventional	pivot
14	2010	Kimberly, Twin Falls	silt loam	4.5m × 12.5m	strip, conventional	solid set sprinkler

Table 3. Site-year soil sampling and nitrogen fertilizer information.

Site	Soil Sample Depth *m*	Residual Soil N Supply *kg N ha^{-1}*	Fertilizer N Rates *kg N ha^{-1}*	Total N Supplies *kg N ha^{-1}*	N Source	N Application Time
1	0.91	175	0,55,127,131	175, 230, 301, 373	Ammonium Nitrate	V2.1
2	0.91	134	0,84,168,252	134, 218, 302, 386	Urea	V2.1
3	0.91	134	0,84,168,252	134, 218, 302, 386	Urea	V2.1
4	0.61	104	0, 56, 112, 168, 224	104, 160, 216, 272, 328	UAN (32% N)	pre-plant
5	0.91			170, 205, 239, 273	Urea	V2.1
6	0.61			195, 236, 264, 308	Urea	V2.1
7	0.91	183	25,29,63,99	207, 212, 245, 281	Urea	V2.1
8	0.91	84	86,120,153,188	170, 204, 237, 271	Urea	V2.1
9	0.91	115	86,129,171,214	202, 244, 287, 329	Urea	V2.1
10	0.91	165	12,16,74,155,276	177, 180, 239, 319, 440	Urea	V2.1
11	0.91	100	0,57,110,212,289	100, 157, 209, 311, 389	Urea	V2.1
12	0.91	64	0,105,190,274,402	64, 169, 254, 338, 466	Urea	V2.1
13	0.91	177	0,5,57,111,192	177, 183, 241, 301, 392	Urea	V2.1
14	0.91	67	0, 62, 109, 156, 227	67, 129, 179, 224, 297	UAN (32% N)	V 4.1

N Application

Although the level of the main variable (N supply, fertilizer N + spring soil residual NO_3-N and NH_4-N) being evaluated varied across the site-years, each site had at least four levels of N supply covering a predicted range to capture the response function. Sites 1, 2, 3, 4, 11, 12, 13 and 14 contained a no fertilizer control (Table 3). Sites 5, 6, 7, 8, 9, and 10 set the lowest N supply was set to provide a Nr of 2.5 kg N Mg^{-1} beets based on historic yield goals between 67 and 78 Mg ha^{-1} (Table 3).

The various N fertilizers (Table 3) were incorporated immediately after application either with tillage (site 4) or with at least 13 mm of irrigation water (remaining sites). All fertilizer was applied prior to the 6-leaf stage

Prior to N fertilizer treatment applications in spring, 3 to 18 cores were taken from each replication block in 0.3 m increments to a depth of 0.6 or 0.9 m (sites 4 and 6 were sampled to 0.6 m due to a restrictive layer at that depth). At each site, soil cores from across each replication block were composited by depth increment. Soil samples were analyzed for nitrate-N (NO_3-N) and ammonium-N (NH_4-N) at either the USDA-ARS research laboratory or a commercial soil testing laboratory using established protocols.

Harvest and Analysis

Root yield was determined from each plot using a load cellscale mounted to a plot harvester. From the roots harvested, two samples (at least 12 kg each) were bagged and analyzed at the TASCO tare lab for percent sugar and other quality parameters. Percent sugar was determined using an Autopol 880 polarimeter (Rudolph Research Analytical, Hackettstown, NJ), a half-normal weight sample dilution, and aluminum sulfate clarification method [ICUMSA Method GS6-3 1994] (Bartens, 2005). Conductivity was measured using a Foxboro conductivity meter Model 871EC (Foxboro, Foxboro, MA) and nitrate was measured using a Model 250 multimeter (Denver Instruments, Denver, CO) with Orion probes 900200 and 9300 BNWP (Krackler Scientific, Inc., Albany, NY). Recoverable sucrose yield per ton of roots was estimated by: [(percent extraction)(0.01)(gross sucrose/ha)]/(t/ha), where percent extraction = 250 + [[(1255.2)(conductivity) – (15000)(percent sucrose - 6185)]/[(percent sucrose)(98.66 – [(7.845)(conductivity)])]] and gross sucrose (t/ha) = (gross root yield, t/ha)(percent sucrose)(0.01)(1000 kg/t).

Statistical Analysis and Calculations

Statistical analyses and calculations were conducted separately for each site-year. Analysis of variance was conducted for N supply treatment main effects on selected production factors (root yield, ERS yield, root sucrose concentration, root brei nitrate concentration, and N use efficiency) using a randomized block design model in Statistix 8.2 (Analytical Software, Tallahassee, FL). Nitrogen use efficiency was defined as the quantity of sucrose produced per kg N supply (fertilizer N + spring soil residual inorganic N).

Evaluation of Nr

For site-years with significant N supply main effects on ERS yield, the maximum ERS yield was determined by comparing adjacent numerically ordered means using the least significant difference method (LSD) at the 0.05 probability level. For each site-year with no significant N supply main effect on ERS yield, the ERS yield at the lowest N supply was considered the maximum. For each site-year, the Nr at maximum ERS yield was calculated:

(1) $Nr_{@m}$ (kg N Mg^{-1} beet) = $RY_{@m}$ / N $Supply_{@m}$

Where $Nr_{@m}$ = site-year Nr at maximum ERS yield, $RY_{@m}$ = site-year RY obtained at maximum ERS yield, and N $Supply_{@m}$ = site-year N supply at maximum ERS yield.

For each site-year, differences between N supply at maximum ERS yield and recommended past N supplies based on selected published N requirements were evaluated (Excess N Fertilizer). For each site-year, differences between N costs at maximum ERS yield and recommended past N supplies based on selected published N requirements were also evaluated (Excess Fertilizer Cost). The past Nr values used were 3.5 and 4 kg N Mg^{-1} ($Nr_{3.5}$ and Nr_4), which were selected from lower end of latest published recommendations (Table 1) and have been commonly used for past recommendations.

(2) Excess N Fertilizer (kg N ha^{-1}, @ $Nr_{3.5}$ and Nr_4) = Recommended Past N Supply (kg N ha^{-1}, @ $Nr_{3.5}$ and Nr_4) - N Supply at Maximum ERS Yield

(3) Excess N Fertilizer Cost (\$ ha^{-1}, @ $Nr_{3.5}$ and Nr_4) = Excess N Fertilizer (kg N ha^{-1}, @ $Nr_{3.5}$ and Nr_4) × N price (\$ kg^{-1} N)

Nitrogen fertilizer price was the average N price paid by consumers based on urea ammonium nitrate from 2009 to 2014 in the U.S. Pacific Northwest (\$2.05 kg^{-1} N; USDA-NASS, 2015).

RESULTS AND DISCUSSION

ERS Yield Response to N supply and Evaluation of Nr

Evaluation of Nr in sugarbeet from the data presented in this paper will be on the basis of ERS yield rather than root yield since production of sucrose is the most important yield factor. Nitrogen supply had significant effects on ERS yields for 6 of the 14 site-years (Table 4, Figure 2). Therefore, there were no ERS yield responses above the minimum N supply for 8 of the site-years (Table 4, Figure 2). In this paper, the terms 'responsive' (6 site-years; 1, 3, 5, 8, 12, and 14) and 'non-responsive' (8 site-years; 2, 4, 6, 7, 9, 10, 11, and 13) will be used to describe these sites relative to ERS yield response to N supply. For the non-responsive sites, the maximum ERS yield was obtained at the lowest N supply. However, the actual N supplies re-

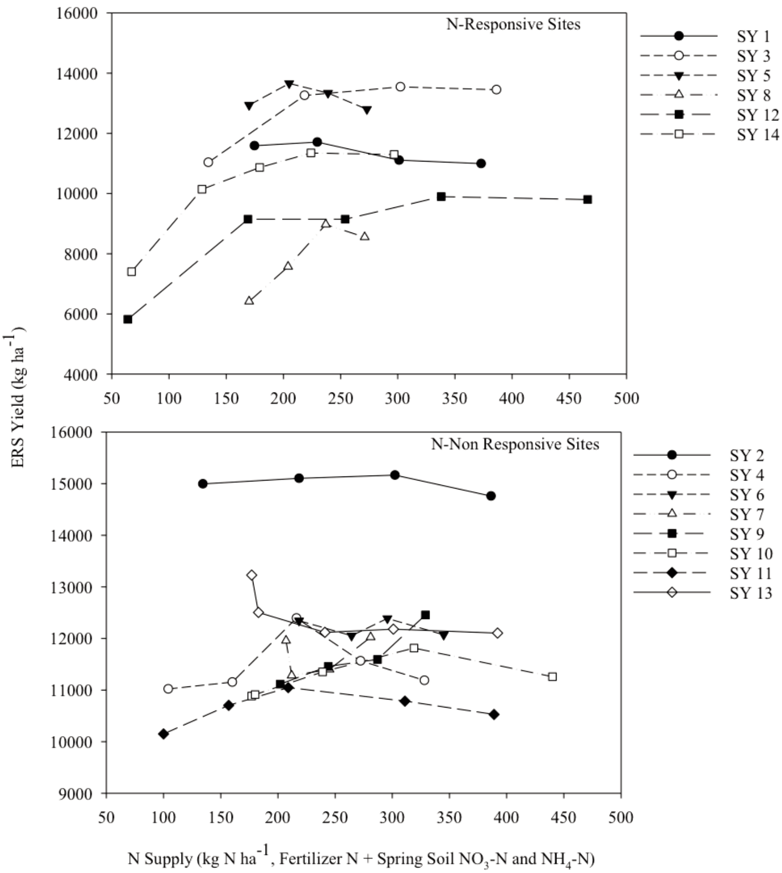
Table 4. Probability values (P>F) from analysis of variance for measured yield related factors for each site-year.

Year	ERS	Root Yield	Root Sucrose	Brei Nitrate	NUE
1	**0.008**	0.434	**<0.001**	---	**<0.001**
2	0.630	**0.038**	**<0.001**	**<0.001**	**<0.001**
3	**<0.001**	**<0.001**	**0.018**	**<0.001**	**<0.001**
4	0.342	0.279	0.061	**0.003**	**<0.001**
5	**0.019**	**0.013**	0.103	**0.028**	**<0.001**
6	0.954	0.676	0.195	0.114	**<0.001**
7	0.899	0.927	0.658	0.702	0.076
8	**<0.001**	**<0.001**	0.927	0.840	0.066
9	0.899	0.716	0601	0.150	**0.043**
10	0.173	0.142	0.983	0.360	**<0.001**
11	0.286	**0.001**	**<0.001**	**<0.001**	**<0.001**
12	**<0.001**	**<0.001**	0.285	0.877	**<0.001**
13	0.534	0.837	0.105	**0.001**	**<0.001**
14	**<0.001**	**<0.001**	0.330	0.054	**<0.001**

sulting in maximum ERS yields are not known because they occurred at levels less than the lowest N supplies. Of the 8 non-responsive site-years, 4 site-years had the lowest N supply as a non-fertilized check (site-years 2, 4, 11, 12) meaning that residual inorganic N and mineralized N were sufficient to obtain maximum ERS yield. For site years 2, 4, 11, and 12 the range of residual inorganic N from the non-fertilized check plots was 64 to 134 kg N ha^{-1} (Table 3). Although much of the past field management for the sites is not known, the residual inorganic N is likely from a combination of mineralized N, past fertilizer and/or manure applications. For analysis and discussion purposes in this paper, at the N non-responsive sites, we assume that maximum ERS yield was obtained at the lowest N supply. ERS yield in all of the responsive sites increased with increasing N supply until plateauing or decreasing except site-year 1, which decreased with increasing N supply. The greatest ERS yield for site-year 1 was at the lowest N supply. Therefore, only 5 of the 14 site-years had a positive response to N supply.

The average $Nr_{@m}$ across all site-years was 2.25 kg N Mg^{-1} beet and ranged from 1.4 to 3.7 kg N Mg^{-1} beet (Figure 3). For all site-years, $Nr_{@m}$ was less than Nr_4, and except site-year 8, less than $Nr_{3.5}$. All site-years except 8, has an $Nr_{@m}$ at or below 2.8 kg N Mg^{-1} beet. The N supply requirements to maximize ERS yield across the site-years were much lower than requirements from the Idaho CFEP which are the basis of the 2009 University of Idaho N recommendations for sugarbeet (Stark et al., 1997; Moore et al., 2009). The data

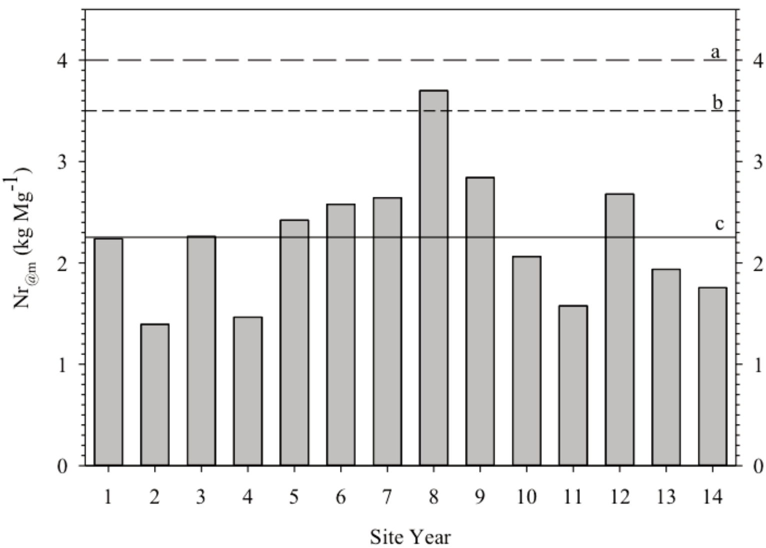
Figure 2. Estimated recoverable sucrose (ERS) yield of sugarbeet versus N supply for responsive and non-responsive sites (Table 4). Data points are the treatment means.



from CFEP were collected between 1994 and 1997; therefore changes in variety genetics and management practices could have resulted in the differences in Nr. The results of the data set presented in this paper suggest that Nr values can be reduced compared to previous recommendations. An upper Nr of 2.8 kg N Mg^{-1} beet would be a conservative value. It is likely that if growers are willing to evaluate sugarbeet production versus N supply over time in their fields they could fine tune the Nr on a site-specific basis.

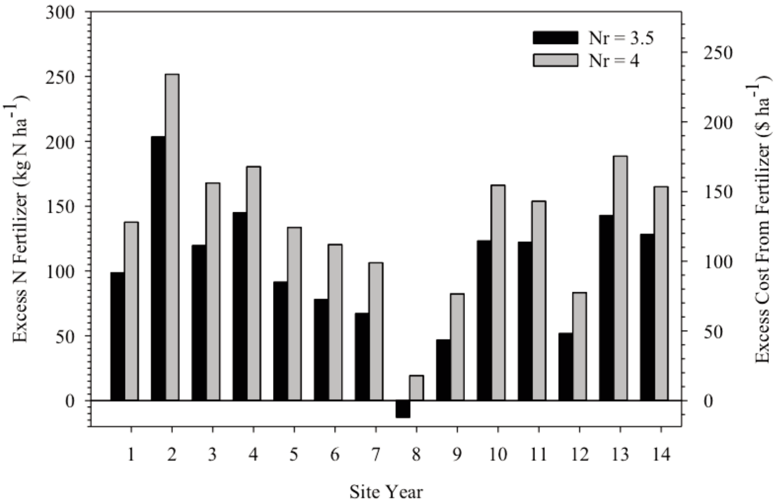
Over all 8 non-responsive sites, the average quantity of excess N

Figure 3. Sugarbeet nitrogen requirement (Nr) at the maximum estimated recoverable sucrose (ERS) yield for each site-year ($Nr_{@m}$). a) TASCO upper Nr range, b) Historical University of Idaho Nr low range, and c) Site year mean $Nr_{@m}$. Each bar is the mean of 4 to 8 site year replications.



fertilizer applied at a Nr of 3.5 compared to the lowest N supply at each site-year was 166 kg N ha^{-1}, with a range of 47 to 203 kg N ha^{-1} (Figure 4). These quantities of N had an average economic cost, based on an N price of $2.05 kg^{-1} N (average price for N as urea ammonium nitrate in the Pacific Northwest U.S. from 2009 to 2014), of $108 ha^{-1}, with a range of $44 to $189 ha^{-1} (Figure 4). Across all 8 non-responsive sites, the average quantity of excess N fertilizer applied at a Nr of 4 compared to the lowest N supply at each site-year was 156 kg N ha^{-1}, with a range of 82 to 252 kg N ha^{-1} (Figure 4). These quantities of N had an average economic cost of $145 ha^{-1}, with a range of $77 to $234 ha^{-1} (Figure 4). Nitrogen supplied in-season by N mineralization from organic N sources was likely the cause of the non-responsive sites. The inability to accurately predict the rate and timing of in-season soil N mineralization has always been a major source of error in N recommendations for crops. In southern Idaho, in-season N mineralization has been shown to be a significant supply of N to sugarbeets (Westermann and Carter, 1975; Carter et al., 1976). Mineralization capacity of N in soils can also vary significantly across soil types, locations, and climatic conditions (Stanford and Smith, 1972; Carter et al., 1976), thus explaining that 6 of the site-years

Figure 4. Excess N fertilizer amount and cost (equations 2 and 3) for each site-year at nitrogen requirements (Nr) of 3.5 and 4 (past recommended Nr value ranges) for sugarbeet.



were responsive while the remaining 8 were non-responsive. The data show that in order to further fine tune N fertilizer applications to sugarbeet in the Pacific Northwest, accurate prediction of in-season N mineralization capacity from soils is needed. In south central Idaho, an increasing percentage of the sugarbeet production area will have a manure application history due to the high concentration of dairy cows. Mineralization from both manured and non-manured fields will need to be addressed.

Root yields responded similar to N supply as with ERS yield. N supply had significant effects on root yields for 7 out of the 14 site-years (Table 4). Of the 7 responsive site-years, 5 also had significant responses of N supply on ERS yields (Table 4).

Brei Nitrate Concentration and Sucrose Concentration

Brei nitrate is a measure of N related impurities in sugarbeet roots. It has been related to reduced sucrose concentrations and decreased sucrose extraction. In the TASCO Sugarbeet Growers Guide Book, it is stated that sucrose concentration decreases by approximately 0.5% for every 100 mg brei nitrate kg^{-1}, and above average sucrose concentrations are likely at brei nitrate concentration below 200 mg kg^{-1} (TASCO, 2015). Nitrogen supply had a significant effect on sucrose concentrations for 4 out of the 14 site-years (Table 4, Figure 5). In general, for the 4 site-years where N supply affected sucrose concentrations, as N supply increased (across entire N supply

Figure 5. Sugar and brei nitrate concentrations versus N supply for 14 site years in sugarbeet. Regression models were fit to the significant relationships (Table 4).

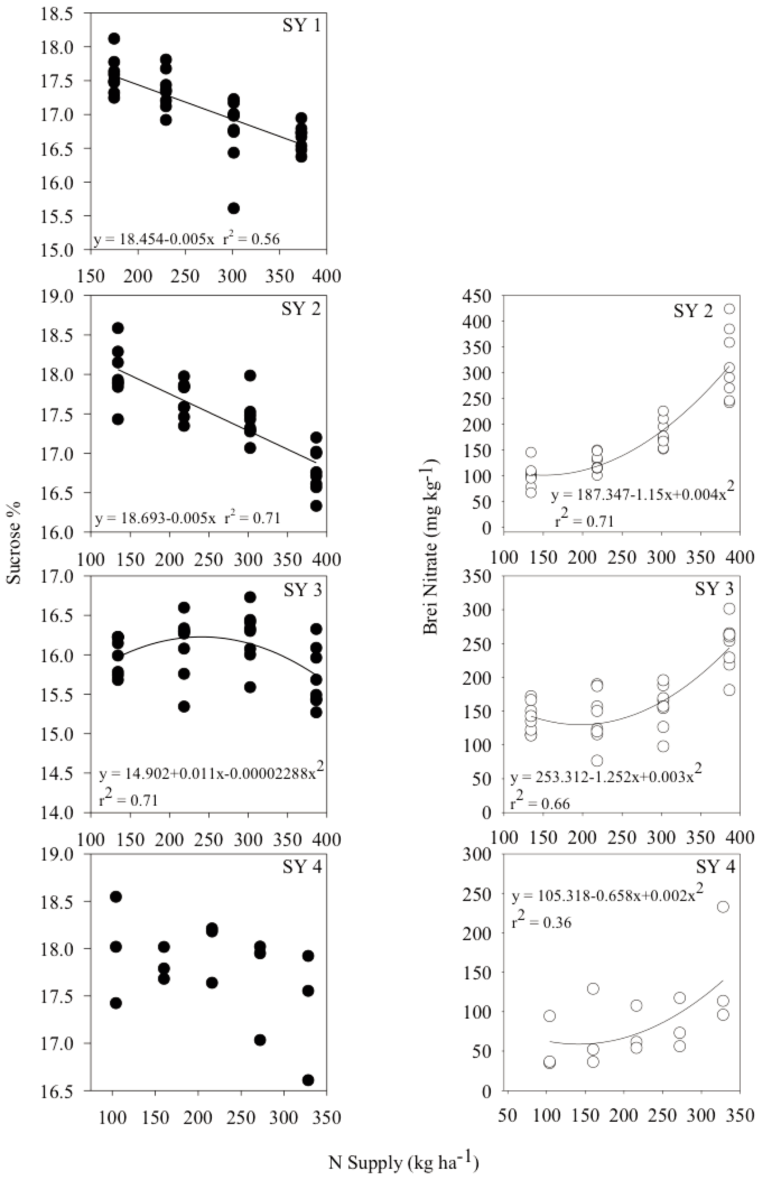
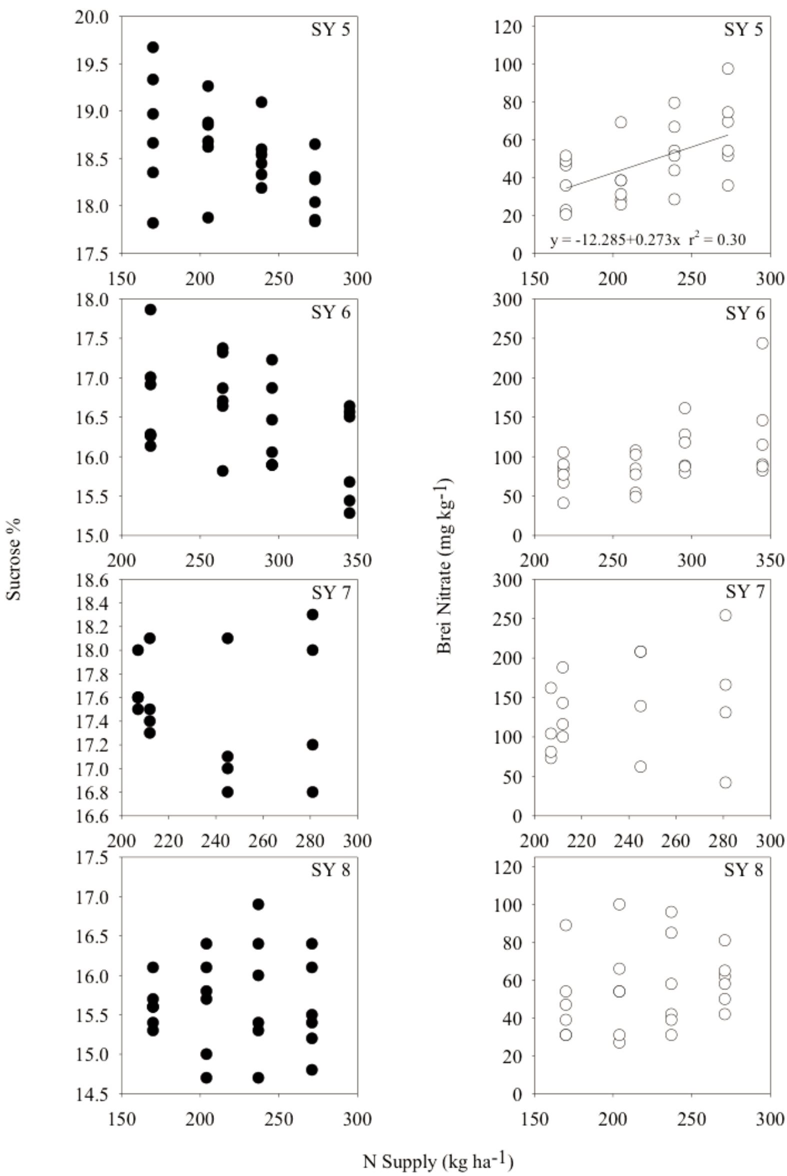


Figure 5 *Cont.* Sugar and brei nitrate concentrations versus N supply for 14 site years in sugarbeet. Regression models were fit to the significant relationships (Table 4).



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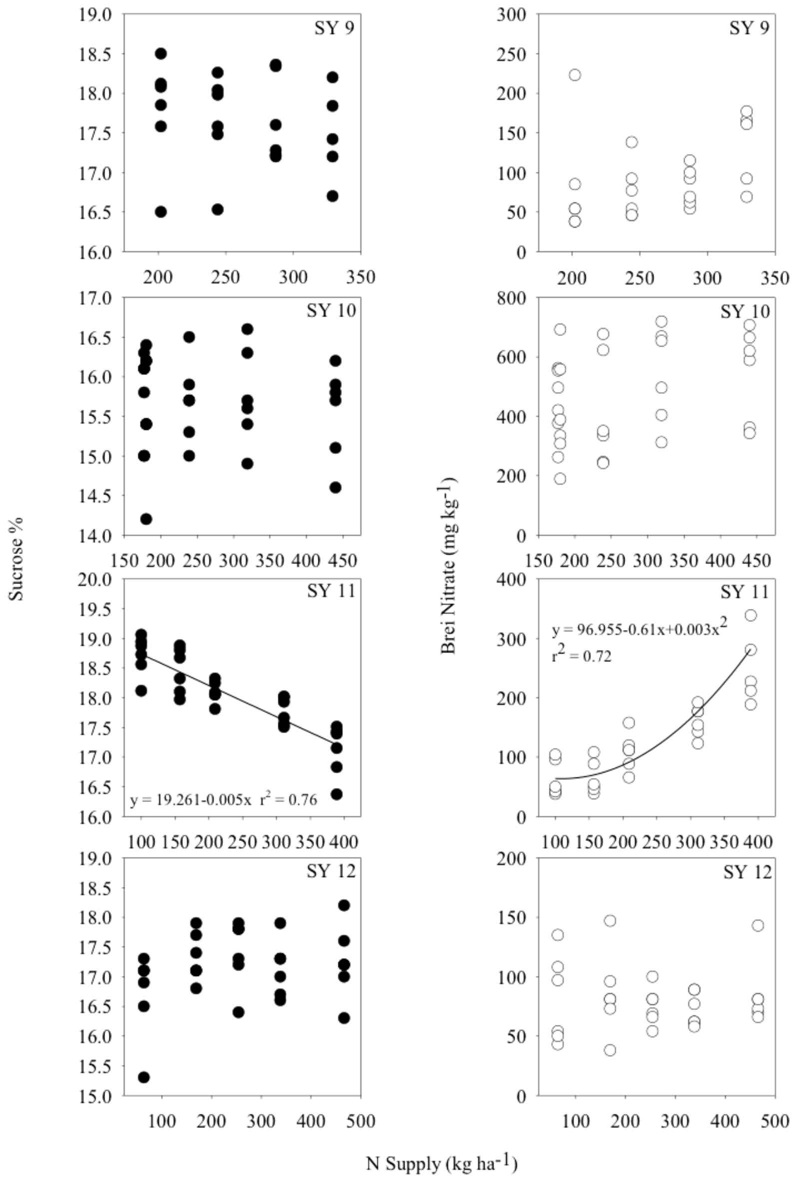

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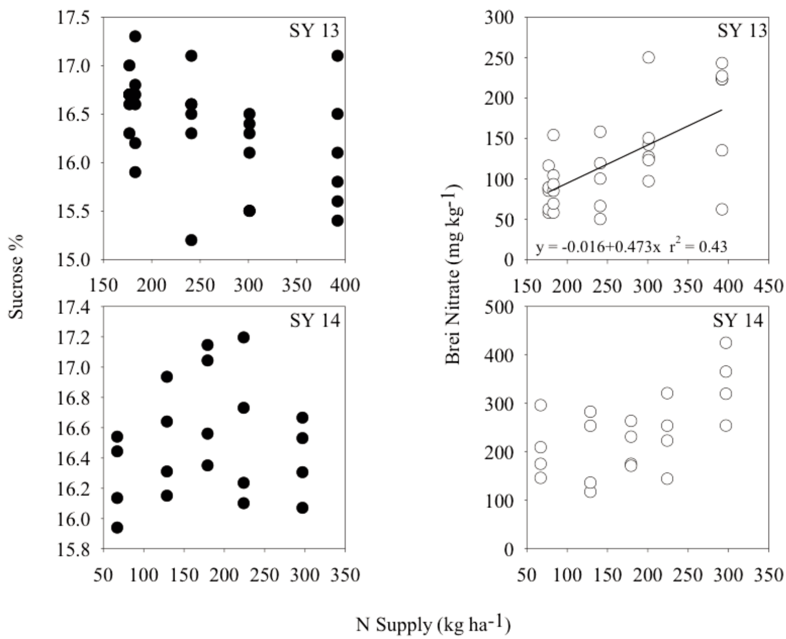


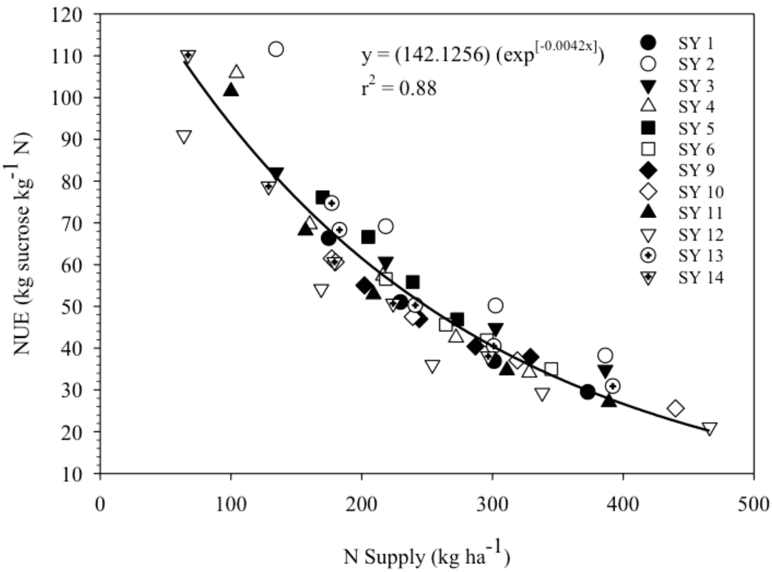
range), sucrose concentrations decreased at a rate of 0.005% kg^{-1} N (Figure 5). For the site-years (4, 5, 6, 7, 8, 9, 10, 12, 13, 14) with no significant relationship between N supply and sucrose concentrations, the average sucrose concentrations were 17.8, 18.5, 16.5, 17.5, 15.6, 17.6, 15.7, 17.2, 16.4, and 16.5%, respectively.

N supply had a significant effect on brei nitrate concentrations for 6 out of the 13 site-years (Table 4, Figure 5, brei nitrate concentrations were not measured for site-year 1). In general, for the 6 site-years where N supply affected brei nitrate concentrations, as N supply increased (across entire N supply range), brei nitrate concentrations increased (Figure 5). Based on regression models, the range of brei nitrate concentrations for site-years 2, 3, 4, 5, 11, and 13 were 105 to 339, 139 to 217, 59 to 105, 34 to 62, 66 to 314, and 84 to 185 mg kg^{-1}, respectively. Only 3 site-years (2, 3, and 11) had significant N supply effects on both sucrose and brei nitrate concentrations (Table 4, Figure 5). For the 7 site-years where N supply did not affect brei nitrate concentrations (6, 7, 8, 9, 10, 12, and 14), the average brei nitrate concentrations across all N supplies were 99, 136, 56, 91, 533,

Table 5. Mean estimated recoverable sucrose yield (ERS), root yield, and nitrogen requirement (Nr) at N supplies for each site year. The least significant difference (LSD) method was used to compare numerically adjacent ERS yields to determine maximum ERS yields. Bolded rows for each site year represent the N rate at which maximum ERS yields were obtained.

Site Year	N Supply † *kg ha^{-1}*	ERS *kg ha^{-1}*	Root Yield *Mg ha^{-1}*	Nr *kg Mg^{-1}*
1	**175**	**11590a**	**78.1**	**2.2**
	230	11710a	80.7	2.8
	301	11108b	79.6	3.8
	373	10996b	79.8	4.7
LSD		453		
3	134	11037b	81.6	1.6
	218	**13263a**	**96.6**	**2.3**
	302	13546a	98.1	3.1
	386	13451a	101.9	3.8
LSD		560		
5	170	12940b	79.6	2.1
	205	**13662a**	**84.7**	**2.4**
	239	13340ab	83.6	2.9
	273	12802b	82.1	3.3
LSD		554		
8	170	6416c	46.3	3.7
	204	7570b	54.4	3.7
	237	**8972a**	**64.1**	**3.7**
	271	8552ab	61.9	4.4
LSD		1002		
12	64	5823b	41.7	1.5
	169	**9147a**	**63.1**	**2.7**
	254	9150a	62.9	4.0
	338	9898a	68.9	4.9
	466	9804a	68.3	6.8
LSD		1562		
14	67	7404c	55.0	1.2
	129	**10142b**	**73.4**	**1.8**
	179	10866ab	77.5	2.3
	224	11350a	82.0	2.7
	297	11297a	82.9	3.6
LSD		780		

Figure 6. Sugarbeet N use efficiency (NUE) versus N supply for site years with significant N supply main effects (Table 4). Regression model was fit to all data. Points represent individual plot values.



80, and 238 mg kg^{-1}, respectively. Looking at the brei nitrate concentrations across all site-years, there is very little evidence that increasing N supply (fertilizer N at the rates in these studies plus residual soil spring inorganic N) had a large effect on brei nitrate concentrations. When N supply affected brei nitrate concentrations, the highest concentration was 339 mg kg^{-1}, while when N supply did not affect brei nitrate concentrations, the highest average concentration across N supplies was 533 mg kg^{-1}. Potential reasons for the lack of a relationship between N supply and brei nitrate concentration at many of the site-years could be variable in-season soil N mineralization rates and varietal/environmental interactions. Available soil N in late summer may have a greater effect on brei and sucrose concentrations than available soil N at planting time.

Nitrogen Use Efficiency

Nitrogen supply had significant effects on NUEs for all site-years except 7 and 8 (Table 4). For the 12 site-years with significant relationships between N supply and NUEs, NUE was highly correlated to N supply (Figure 6). The relationship spans over multiple years, locations, varieties, cultural practices, climates, and soil types, indicating that the model could be used to estimate NUE across the Pacific Northwest growing area over the range of N supplies covered in this study (64 to 466 kg N ha^{-1}). The NUE at the N supplies that produced maximum ERS yields for each site-year ranged from 56.8 to 93.4 kg sucrose kg^{-1} N, with an average of 71.4 kg sucrose kg^{-1} N. At a yield goal of 78 Mg ha^{-1}, reducing the Nr from 3.5 kg N^{-1} Mg beet to 2.8 kg N^{-1} Mg beet will increase NUE by 26%.

The relationship between N supply and NUE for site-years 7 and 8 were not significant at the 0.05 probability level but were significant at the 0.10 probability level. However, the data from these two site years were excluded from the regression model. The average NUE for site-years 7 and 8 were 50.1 and 36.1 kg sucrose kg^{-1} N, respectively.

CONCLUSIONS

Estimated recoverable sucrose yields did not respond to increasing N supply (applied + residual) for 8 of the 14 site-years indicating residual N from past applications and in-season N mineralization likely supplied significant amounts of N to the growing sugarbeet crop. Continued research is needed to allow better predictions of in-season soil N mineralization (from manured and non-manured soils) dynamics to improve N management and recoverable sugar yields. The data from this paper suggest that the Nr values can be reduced in the Pacific Northwest sugarbeet production area compared to past recommendations resulting in significant N fertilizer and cost savings. The Nr values producing maximum ERS yields for 13 of the 14 site-years were all below 2.8 kg N^{-1} Mg beet, which is much lower than the past University of Idaho and TASCO published Nr values of 3.5 and 4 kg N^{-1} Mg beet. Overall, brei nitrate concentrations and sucrose were only occasionally influenced by N supply. A strong relationship between N supply and NUE across all site-years indicated the relationship could be used to predict NUE over various N supply levels over the Pacific Northwest sugarbeet production area. Since NUE decreases with N supply, reducing the Nr as recommended in this paper will improve NUE compared to past recommendations.

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