Optimum Nitrogen Rates for Maize and Wheat in North Carolina

Robert Austin, Deanna Osmond,* and Shelby Shelton

ABSTRACT

Nitrogen decision making and the selection of the “right” N rate in wheat (Triticum aestivum L.) and maize (Zea mays L.) are difficult due to complex interactions in the N cycle with weather, management, and genetics. An adaptive management approach utilizing farmer networks and participatory learning was established to refine N rate decisions. On-farm trials were established to reflect grower N rate with additional treatments of ±25% N. In 79 site-years of wheat, N-25%, Nstd, and N+25% rate treatments were best in 37, 35, and 28% of the trials, respectively. In 100 site-years of maize, N-25%, Nstd, and N+25% rate treatments were best in 58, 30, and 12% of the trials, respectively. Grower’s selected N rates in wheat were similar to recommendations from the North Carolina Realistic Yield Expectation (RYE) database while maize N rates were an average 48 kg ha⁻¹ higher; however, N-25% rates, which were best 58% of the time, were similar to RYE N rate. Doppler-based estimates of total precipitation from the National Weather Center explained 90% of the average maize yield variability. However, site-yield was independent of location, N rate, and total precipitation. Measures of performance (N factor productivity and N balance) varied with achieved yields but indicate most growers apply N adequate to maintain organic N lost through mineralization. Results suggest that improved approaches to N rate selection and N efficiency will likely require in-season adjustments to yield-based N rates that incorporate local management and environmental conditions throughout the growing season.

Core Ideas

- Yield level and response is independent of location, N rate, and total precipitation.
- Doppler-based rainfall estimates help explain seasonal trends in yield.
- Growers often select N rates greater than recommended for maize but not wheat.

Published in Agron. J. 111:2558–2568 (2019)
doi:10.2134/agronj2019.04.0286
Available freely online through the author-supported open access option

© 2019 The author(s).
This is an open access article distributed under the CC BY license (https://creativecommons.org/licenses/by/4.0/)
recommendations and yields are often multiplied by the internal N demand per bushel or unit yield (Morris et al., 2018). Other states determine the average of recent yields and add 10 to 20% to that value (Reitsma et al., 2008; Shapiro et al., 2008; Rehm and Schmitt, 1989) or advocate for a maximum return to nitrogen (MRTN) approach for a cropping system, selected region, and price ratio (Sawyer et al., 2006). More arid areas, such as Kansas or Texas often include a measure of soil nitrate with a recommended N rate derived from a yield goal (Dinkins and Jones, 2007; Schmitt et al., 2008). In addition to straight yield goal calculations, most states have modified the Stanford equation to meet specific agro-environmental and interpretive conditions (Morris et al., 2018); North Carolina is no exception. Alternatives to the yield-based methods exist and include recommendations based on similar site–soil–yield characteristics (Vanotti and Bundy, 1994), optical crop sensors for in-season management of N (Kitchen et al., 2010; Dellinger et al., 2008; Scharf and Lory, 2009), and computer simulations that combine crop–soil–weather information into model-based recommendations (Melkonian et al., 2008; Setiyono et al., 2011).

More rigorous nutrient management planning was required to meet state regulations and state and/or federal cost-share requirements in North Carolina. As such, the state of North Carolina established crop yield goals and associated N rates in the early 2000s. The North Carolina RYE database was developed and yield goals were established for 32 different crops on hundreds of soil series across the physiographic regions (coastal plain, piedmont, and mountains) (North Carolina Nutrient Management Workgroup, 2017). Data development was a collaboration between North Carolina State University, the Natural Resource Conservation Service, the North Carolina Department of Agriculture and Consumer Services, the North Carolina Division of Soil and Water Conservation, and many local partners and farmers. The data tables were updated in 2015 for higher-yield maize varieties (Rajkovich et al., 2015) and recent data confirmed maize and wheat N recommendations (Rajkovich et al., 2017).

Morris et al. (2018) have detailed the strengths and weaknesses of N recommendations made from yield goals and have suggested that adaptive N management be used by farmers to potentially augment and refine N rate decision-making. Adaptive management has been defined by the multi-state northeast extension database, (iii) investigate the use of simple N metrics (N factor productivity and N balance) relative to N rate selection for maize and wheat, and (iv) provide farmers with detailed soil and yield data in a group setting to discuss results and selection of N rates.

METHODS AND MATERIALS

Field Study

On-farm N trials began in 2013 and continued through 2017. Farmers were initially recruited from Sampson and five surrounding (Bladen, Cumberland, Duplin, Harnett, Johnston, and Wayne) counties in North Carolina for the 2013 growing year. Initially personnel in the Crop and Soil Sciences Department at North Carolina State University and a certified crop consultant in the area conducted on-farm trials in association with farmers. In 2014, more crop consultants were added along with 10 new coastal plain counties: Craven, Edgecombe, Green, Halifax, Jones, Lenoir, Nash, Northampton, Robeson, and Wilson. Additional counties (Beaufort, Bertie, Camden, Gates, Pasquotank, and Perquimans) and consultants were again added in 2015. In 2016, North Carolina State University researchers discontinued research with their farmers and independent crop consultants ran the network with supervision by North Carolina State University through 2017.

Farmer participation varied throughout the program. Trials run by personnel from North Carolina State University enlisted farmers using an open search process lead by North Carolina Cooperative Extension, while additional farmers were recruited by local county extension agents. Crop consultants were added later in the program to expand the farmer network and recruitment included business clients and personal farms. Because yield was generally collected using a yield monitor, the project funder provided full or partial installations of yield monitoring and mapping equipment to 16 initial growers. Farmers recruited later in the project were expected to have yield monitors.

The number of trials varied each year depending on interest from farmers, capacity of North Carolina State University researchers and crop consultants, funding, and weather. There were 31 producers in 2013 on a total of 17 ha, 80 producers in 2014 on 104 ha, 71 producers in 2015 on 91 ha, 28 producers in 2016 on 36 ha, and 19 producers in 2017 on 25 ha. Trials were conducted across 23 counties in the coastal plain region of North Carolina. Two crops—maize and wheat—were used in the N-rate trials. A total of 141 wheat trials and 131 maize trials were attempted, however not all trials were included in the analysis. The results presented represent 79 site-years in wheat and 100 site-years in maize (Fig. 1). Reasons for exclusion varied but included mechanical or technical issues during harvest, sprouting of wheat grain in seed heads, data loss, or corruption during transfer, incomplete or improperly setup experimental design, use of irrigation, application of manures, and incorrect N rates in replicated strips. Specifically, 2013 wheat trials were excluded due to a confounding of data during harvest and omitted in 2016 and 2017 because of low enrollment due to wet field conditions and limited statistical power. Although yield was recorded using a yield monitor for the majority of trials, five trials used a weigh wagon to record yield.

Trials were setup as 13 equal-width strips prior to N fertilization of four blocks of three rates: the farmer’s standard N rate (Nstd), 25% more than the standard rate (N+25%), 25% less than the standard rate (N-25%) and one calibration strip used for N
rate adjustments. The three N-rate treatments were randomized within each block. Trial boundaries were mapped using a Trimble GeoXT GPS receiver (Trimble, Sunnyvale, CA) connected to the North Carolina Virtual Reference System network. Strip lengths were a minimum of 75 m, while strip width ranged from 3 to 12 m depending on plant spacing, crop, and combine header width. The underlying NRCS map units (USDA-NRCS SSURGO2, 2017) were identified in a Geographic Information System (GIS) and their respective areas calculated.

As a consequence of using the farmers’ standard N management for the baseline treatment, the amount and timing of N applications varied. Farmers fertilized wheat and maize as they normally would when planting; farmers in North Carolina almost always split apply N (Osmond et al., 2013a, 2013b). Top-dress applications in wheat and side-dress applications in maize of N fertilizer were applied as liquid urea ammonium nitrate at GS30 for wheat and V6 for maize by university personnel or crop consultants. University personnel applied fertilizer with a 10.7-m Reddick (Reddick Equipment Company of North Carolina, Inc., Williamston, NC) ground-driven boom sprayer equipped with a John Blue pump (CDS-John Blue Company, Huntsville, AL) and VariTarget 9 (SprayTarget, Rosemount, MN) variable rate flat fan nozzles. The pump was calibrated between each treatment and a Trimble guidance system was used as trial layouts dictated. Crop consultants applied fertilizer using either business or farmer-owned equipment and standard calibration procedures were followed.

Crop management was based on farmers’ standard production practices and metadata collected included: variety, seed population, prior crop, tillage practice, and planting, application, and harvest dates. In wheat, 54% of the trials followed maize, 24% cotton (Gossypium hirsutum L.), 12% tobacco (Nicotiana tabacum L.), and peanut (Arachis hypogaea L.), and the remaining 10% soybean (Glycine max (L.) Merr.), sweet potato (Ipomoea batatas (L.) Lam.), or sorghum (Sorghum bicolor (L.) Moench). Tillage included 65% conventional, 27% no till, and 8% strip till. The majority of growers (60%) planted between 155 and 200 kg ha\(^{-1}\) (140–180 lbs acres\(^{-1}\)) of wheat seed with 75% drilled at a 2.3 m spacing and the remaining 25% broadcast. In maize, more than 63% of the trials followed soybean with the remaining trials planted after cotton (15%), peanut (10%), corn (Zea mays L.) (8%), or sweet potato or tobacco (4%). Tillage operations included 44% strip till, 39% conventional, and 17% no till. Populations ranged from 57,000 to 84,000 seeds ha\(^{-1}\) (23,000–34,000 seeds acre\(^{-1}\)) with most trials planting between 64,000 to 74,000 maize seeds ha\(^{-1}\) (26,000–30,000 seeds acre\(^{-1}\)). Seed variety varied but was typically classified as mid-to-long season varieties.

At every trial location and prior to planting, soil samples were collected by block and sent to the North Carolina Department of Agriculture and Consumer Services (NCDA&CS) for testing and analysis (Hardy et al., 2014). Each sample included 15 to 20 cores collected at an 20 cm depth. Soil test results collected at each location indicated that nutrient levels were sufficient across trial locations with more than 95% within recommended levels (Table 1).

All participants had yield monitors. Calibration was performed using manufacturers’ recommended calibration procedures with help from university personal using a weigh wagon and Dickey John grain moisture tester (DICKEY-john, Auburn, IL). Crop consultants performed similar calibrations with participating farmers before harvest. After harvest, yield data were transferred to university researchers along with the supporting field and management information. The yield data were cleaned of erroneous values and the N treatments joined to the yield data within a GIS. Edge effects observed in the yield data that occur due to start and end pass delays were identified and removed. Before analysis, yield values were adjusted to standard moisture contents of 13.5% for wheat and 15.5% for maize. Processed and cleaned data were uploaded to a relational database (MySQL 5.7, 2015) and further analyzed using R (R Development Core Team, 2008) and SAS statistical software (SAS Institute, 2011).

**Nutrient Performance (Nitrogen Partial Factor Productivity and Partial Nitrogen Balance)**

A trial-by-trial assessment of nutrient performance was conducted using two metrics for N fertilizer efficiency-nitrogen partial factor productivity (PFP\(_N\)) (Cassman et al., 1996) and

---

**Table 1. Summary of 716 soil tests results collected by consultants in the farmer network and analyzed by the North Carolina Department of Agriculture and Consumer Services Soil Testing Division.**

<table>
<thead>
<tr>
<th>Soil property</th>
<th>Min.</th>
<th>First quartile</th>
<th>Median</th>
<th>Mean</th>
<th>Third quartile</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>4.9</td>
<td>5.5</td>
<td>5.8</td>
<td>5.7</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Phosphorus, mg kg(^{-1})</td>
<td>48</td>
<td>91</td>
<td>140</td>
<td>157</td>
<td>202</td>
<td>564</td>
</tr>
<tr>
<td>Potassium, mg kg(^{-1})</td>
<td>27</td>
<td>85</td>
<td>111</td>
<td>128</td>
<td>160</td>
<td>413</td>
</tr>
<tr>
<td>Sulfur index, mg kg(^{-1})</td>
<td>5</td>
<td>12</td>
<td>16</td>
<td>21</td>
<td>22</td>
<td>300</td>
</tr>
<tr>
<td>Calcium, % of CEC</td>
<td>37</td>
<td>51</td>
<td>55</td>
<td>55</td>
<td>59</td>
<td>86</td>
</tr>
<tr>
<td>Magnesium, % of CEC</td>
<td>6</td>
<td>12</td>
<td>15</td>
<td>15</td>
<td>18</td>
<td>25</td>
</tr>
<tr>
<td>Humic matter, %</td>
<td>0.2</td>
<td>0.4</td>
<td>0.6</td>
<td>1</td>
<td>1</td>
<td>6.5</td>
</tr>
<tr>
<td>CEC, meq 100cm(^{-3})</td>
<td>2.7</td>
<td>4.3</td>
<td>5.7</td>
<td>6.3</td>
<td>7.9</td>
<td>15.7</td>
</tr>
</tbody>
</table>
partial nitrogen balance (PNB) (OECD, 2013). The PFPN is the ratio of grain yield to applied N and equates to the amount of grain that is produced using a constant unit of N (e.g., kg grain 1 kg⁻¹ N). It is not the same as NUE but does serve as a simple proxy for comparison when there is no nil fertilizer application treatment to estimate the extra yield in response to added nutrient. The PFPN provides a measure of total agronomic output relative to the utilization of all available N resources in the system. The PFPN was calculated for each N rate, including RYE N rate and best agronomic rate, at each location, and then averaged by crop and year. Averaging allowed comparisons between agronomic best and RYE N rates.

The PNB was used to estimate the amount of N added to the crop in relation to crop needs. It represents the amount of fertilizer N minus the grain N removed at harvest and is calculated by:

\[
\text{Partial N balance} (\frac{\text{kg N}}{\text{ha}}) = \text{Total N applied} (\frac{\text{kg N}}{\text{ha}}) - \text{Grain N} (\frac{\text{kg N}}{\text{ha}})
\]

where the amount of N removed at harvest from grain is calculated as:

\[
\text{Grain N} (\frac{\text{kg N}}{\text{ha}}) = \text{IPNI crop N} (\frac{\text{kg N}}{\text{t grain}}) \times \text{Grain yield} (\frac{\text{t grain}}{\text{ha}})
\]

The PNB was calculated using the N rates for each of the three N treatments and the RYE-based N rate. The removal of N from grain was calculated based on measured yields and published grain N values from the International Plant Nutrition Institute (IPNI, 2014). An IPNI crop removal estimate of 19 kg N t⁻¹ for winter wheat grain (1.9% N) and 12 kg t⁻¹ for corn grain (1.2% N) were used with standard grain moisture contents. Comparisons of the PNB were performed between the grower’s standard practice, the best agronomic rate, and the RYE-based values.

North Carolina Realistic Yield Expectations

Realistic yield expectations and associated N rates were determined from the RYE database (North Carolina Nutrient Management Workgroup, 2017) by crop and soil mapping unit for each trial. The RYE yields and N rates were compared at each site location to compare grower standard practices to recommended rates and provides additional information for the continued updating and verification of the North Carolina RYE data table (Rajkovich et al., 2015).

Statistical Analysis

Due to insufficient N rates, we were unable to generate yield response models or to determine a true agronomic optimum N rate for each trial location. Instead, N rates were compared. Yields were analyzed at site locations as a randomized complete block design using a linear mixed-effects model in R software (Laird and Ware, 1982). Significant yield variation by N treatment was determined using least square means between treatments at a significance level of \( p < 0.10 \). Yield was modeled using treatment as a fixed effect and replication as a random effect. The “best” agronomic N rate was determined for each trial based on the results of the mixed model. The treatment with the highest significantly different yield is reported as the best N rate. If two treatment levels were statistically similar as determined by a Tukey-HSD post-hoc test then the lower of the two N rates was considered the best agronomic rate. If no treatment difference was observed than the \( N_{25\%} \) treatment was considered the best agronomic rate. Trials were combined within spatially clustered regions, by supervising crop consultant, and across years to investigate possible regional or consultant-driven relationships between N rate and grain yield. Summary statistics describing yearly trends in yield and N rates are included.

Rainfall

Rainfall was not directly measured at site locations. Instead, daily 4 km-gridded National Weather Center WSR-88D Doppler-based multi-sensor precipitation estimates (MPE) (Lin and Mitchell, 2005; Kitzmiller et al., 2013) were used to estimate rainfall at each location. To correct known inaccuracies in radar-only rainfall data, MPE is calibrated with routinely available hourly surface gages. The MPE provides the spatial resolution of radar with the increased accuracy of surface gauge networks. The overall accuracy between MPE and surface rainfall is well studied (Young et al., 2000; Young and Brunsell, 2008; Habib et al., 2009) and has improved in recent years with updates to radar equipment and the MPE algorithm. Differences observed at locations are minimized when evaluated over longer time periods with correlations around 80% when monthly totals are considered (Westcott et al., 2008). Validation of the MPE dataset for the period of study was performed against three North Carolina State Climate Office (SCO) weather stations regionally distributed within clusters of on-farm trials. The MPE estimates were validated against measured rainfall on weekly, monthly, and season-long intervals. Seasonal totals reported for wheat are from 1 November to 1 March and for maize from 15 April through 31 August.

RESULTS AND DISCUSSION

Nitrogen Rates

The average N rate selected by growers increased every season. In wheat, \( N_{std} \) increased from 129 to 134 kg ha⁻¹ and in maize from 179 to 213 kg ha⁻¹. Yearly shifts in N rates were largely driven by changes in those participating in the farmer network. Most involved in the program participated for two seasons, then transitioned out. As new participants were added through the use of crop consultants, the location of the trials shifted to different regions. The regions were largely related to the recruitment process used by crop consultants where existing clientele were recruited to participate. Although the N rates selected were not significantly different between seasons, the N rates were statistically different when grouped by their supervising crop consultant and region (Fig. 2).

In wheat, new participants under Consultants D and E increased the average N rates. Beginning in 2015, maize trials were mostly phased-out of the south-central coastal plain (Consultant C) and added to the northeastern region where \( N_{std} \) was higher (Consultant B and E) (Fig. 2). Overall, the grower N rates selected by the group recruited via the regional, open search process and conducted by University personnel (Consultant C) were lower than in the regions where a crop consultant enlisted clients and either supervised or personally conducted the trials (Fig. 3). As such, shifts in the management of the farmer network and the related regionally-based recruitment processes altered the participant makeup on a yearly basis.
These shifts in the grower population account more for the observed upward trend in grower selected N rates than a change in grower practice.

The average selected N rate in wheat ranged from 110 to 150 kg N ha\(^{-1}\) depending on the consultant (Fig. 3) and their associated region in the state (Fig. 2). Participants under consultants D and E (147 kg N ha\(^{-1}\)) were statistically higher than under A, B, and C (119 kg N ha\(^{-1}\)) and located further East in the coastal plain. Individual N rates were typically within 20 kg N ha\(^{-1}\) of the regional average, with the exception of trials run by University personal (C). The open recruitment process resulted in a wider range of selected N rates as compared to trials run by the independent crop consultants.

In maize, the selected N rates averaged 195 kg N ha\(^{-1}\) across all trials but ranged from 178 to 232 kg N ha\(^{-1}\) depending on the consultant (Fig. 2 and 3). The highest N rates were observed in the northern tidewater region of the coastal plain (E) in an area surrounded by mineral-organic and organic soils and typically higher grain production (NASS, 2017). The lowest rates occurred under trials supervised by university personal and recruited by an open process. The majority of rates selected across all consultants were within 50 kg N ha\(^{-1}\) of the regional average.

**Wheat and Maize Yields**

Wheat grain yield at the standard grower N rate averaged 4662 kg ha\(^{-1}\) across all trials and ranged less than 135 kg ha\(^{-1}\) between years (Fig. 4). Within years, the location of the trial had no significant effect on yield. In 2014, yields ranged from 2850 to 7880 kg ha\(^{-1}\) with over half of the trials yielding less than 3800 kg ha\(^{-1}\) or more than 5400 kg ha\(^{-1}\). In 2015, yields ranged between 2000 and 6300 kg ha\(^{-1}\) with fewer trials yielding greater than 6000 kg ha\(^{-1}\). Yields were not significantly different between years and the supervising consultant had no effect on achieved yield.

Grain yield for maize at the grower’s standard rate averaged 10,465 kg ha\(^{-1}\) across all years. A significant year effect was measured between 2013 and 2015 with average yields ranging from 11,754 to 8862 kg ha\(^{-1}\), respectively (Fig. 4). A wet growing season in 2013 resulted in record yields across many parts of the coastal plain and in 2015 major portions of the state underwent severe drought; otherwise there was no year effect on trial yield (Fig. 4). Both site and site-year were highly significant with over half the trials ranging more or less than 2700 kg ha\(^{-1}\) from the yearly average. Yields in the northeast region under consultant E were significantly higher and averaged almost 14,000 kg ha\(^{-1}\). Over this same period, yield data reported to the National Agricultural Statistics Service (NASS, 2017) averaged 2000 kg ha\(^{-1}\) higher than that of any of the other regions included in this study. This data suggest that the higher maize yields in this region are more closely related to the production potential of the region than to management. Variability across sites was similar most years (cv = 30%) with the exception of 2013 where trials were clustered within a single region and rainfall was abundant.

The agronomic best treatments were determined for both crops and summarized in Table 2. In wheat the N\(_{-25\%}\) treatment was the best rate in 37% of the trials, the N\(_{std}\) rate in 35% of the trials, and the N\(_{+25\%}\) rate in 28% of the trials. There was little difference between years despite the slight increase in the average N\(_{std}\) rate and decrease in average yield. Across all trials the best N rate was 132 kg N ha\(^{-1}\), equal to that of the grower’s standard practice. The best N rates resulted in an average wheat yield of 4740 kg ha\(^{-1}\), 190 kg ha\(^{-1}\) more than the average yield recorded as the growers’ standard rate.
In maize the N-25% treatment was the best rate in 58% of the trials, Nstd was best in 30% of the trials, and N+25% the best in 12% (Table 2). The growers’ standard N rate was the best agronomic rate from 21 to 39% depending on the year. In 2013 and 2017 an overall smaller yield response was measured and the N-25% treatment was the best rate in a large majority of trials (65%). The best N rate averaged 171 kg N ha⁻¹ and yielded 10,600 kg ha⁻¹, 22 kg N ha⁻¹ less than the grower’s standard practice with 60 kg ha⁻¹ lower grain yield. In over 85% of the trials, the growers’ standard N rates met or exceeded the required crop need. The highest unmet N needs occurred in more moderate yielding years. Spatially there was no clustering of trials with a significant yield response further supporting previous work on the independent nature of location on yield response (Raun et al., 2011; Dhital and Raun, 2016). Data suggest that in most years the majority of farmers could have achieved a similar yield at the lower rate and that in years with higher than average yield, response to N is lower.

**Rainfall**

The timing and magnitude of precipitation events in rainfall limiting environments has long been known to influence yield (Robins and Domingo, 1953; Denmead and Shaw, 1960; Nielsen et al., 2010) and confound the selection of a single optimum N rate (Shaw and Durost, 1965; Thompson, 1988; Oberle and Keeney, 1990). Because rainfall was not directly measured at trial locations NWS Doppler Radar-based MPE estimates were used. Validation against three North Carolina State Climate Office rain gauge stations located within the network indicate total seasonal rainfall estimates from MPE were within 70 mm of gauged totals in wheat and 40 mm in maize. Gauged rainfall measurements were also highly correlated with MPE estimates where 95% of the seasonal total was explained by MPE estimates in wheat and 83% in maize. Monthly and weekly rainfall totals were significantly correlated to gauged totals with $R^2$ of 0.87 and 0.81 in wheat, and 0.76 and 0.74 in maize (data not shown). In general, MPE performed equally well across station locations and was approximately 10% more accurate in seasons with higher total rainfall.

Across the farmer network average maize yield was highly related to MPE rainfall with 90% of the grain level explained by total seasonal rainfall ($p = 0.025$) (Fig. 5). A 150 mm increase in rainfall resulted in a 2900 kg ha⁻¹ increase in average grain harvested (19 kg ha⁻¹/mm rainfall). The years with the highest recorded rainfall and yields, 2013 and 2017, were also years with statistically different N rates (Table 2). In 2013, 34 kg ha⁻¹ less N was applied than in 2017, yet yields were statically similar with 2013 yielding 852 kg ha⁻¹ more. In both these years over 60% of the participants could have selected the N-25% rate and achieved a statistically similar agronomic yield, a higher percentage than in any of the other years. These results support that in seasons with above average rainfall, N rate had less effect on the overall yield level achieved across the network and that N response was somewhat lower with more growers likely to attain similar yields with lower N rates. Over all but the driest year, growers realized a water use efficiency of 13.0 kg ha⁻¹/
mm rainfall, similar to that identified by Norwood in Kansas (Norwood, 2001) and Ko in Texas (Ko et al., 2009).

On a site-by-site basis and across all seasons rainfall was weakly correlated to both wheat and maize yields across N rates with on average 10% of the variability in yield explained by the total rainfall. In wheat, rainfall had a small but insignificant effect on the relationship between N rate and yield, however in maize, rainfall played an important role. In years with above average rainfall, no relationship between N rate and yield was observed, however in drier years, between 25 and 50% of the yield was explained by the N rate applied at that location.

In wheat, rainfall was similar between seasons averaging 566 mm (Table 3) and uniform between months (< ±25 mm from monthly average of 94 mm). However, when rainfall totals were divided into 2-wk intervals, the period from 15 March to 1 April was significant across all treatment levels in both years. More than 85% of the participants in these 2 yr applied N during this period suggesting the significance of rainfall and N supply on yield at top-dress in wheat.

Rainfall during maize production averaged 617 mm but varied widely by season and location (Table 3). Relatively uniform, widely spread rainfall in 2013 and 2017 resulted in similar seasonal totals and less than a 207 mm difference between any two locations. In contrast, rainfall in 2014, 2015, and 2016 was highly variable with locations differing by as much as 589 mm. Although seasonal totals explained little of the variability in yield, when broken down into 2 wk intervals, the rainfall from 15 June to 1 July was significant (\(p = 0.023\)) to maize grain yield with the N+25% rate showing slightly higher correlation than Nstd and N-25%. Based on reported planting and maturity dates, this period corresponds to tasseling and silking in more than 90% of the trials.

In both wheat and maize, the significant periods of rainfall or drought occurred shortly after the in-season application of N, which are critical times in crop development and for N mobility in soil. Significance during these periods underpins the seasonal nature of N availability and the challenges in N selection under rain-fed environments due to the strong interactions with climate and rainfall. These data support that at the field scale the complex interactions between yield limiting factors and rainfall were distinctive to location and year and sensitive to the timing and magnitude of rainfall events.

### Comparison of North Carolina Realistic Yields and Grower Selected Nitrogen Rates

Grower selected wheat N rates were on average similar to the RYE based N rate but yielded 838 kg ha\(^{-1}\) greater (Table 4). Over half the growers selected N rates ±20 kg ha\(^{-1}\) of the RYE

<table>
<thead>
<tr>
<th>Year</th>
<th>RYE N rate</th>
<th>Best</th>
<th>N-25</th>
<th>Nstd</th>
<th>N+25</th>
<th>RYE yield</th>
<th>Yield difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kg ha(^{-1})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>kg ha(^{-1})</td>
<td>N-25</td>
</tr>
<tr>
<td>2014</td>
<td>132</td>
<td>130</td>
<td>125</td>
<td>120</td>
<td>125</td>
<td>3907</td>
<td>1072</td>
</tr>
<tr>
<td>2015</td>
<td>129</td>
<td>129</td>
<td>124</td>
<td>126</td>
<td>129</td>
<td>3744</td>
<td>1008</td>
</tr>
<tr>
<td>Avg</td>
<td>131</td>
<td>131</td>
<td>129</td>
<td>131</td>
<td>129</td>
<td>3826</td>
<td>1040</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Year</th>
<th>RYE N rate</th>
<th>Best</th>
<th>N-25</th>
<th>Nstd</th>
<th>N+25</th>
<th>RYE yield</th>
<th>Yield difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kg ha(^{-1})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>kg ha(^{-1})</td>
<td>N-25</td>
</tr>
<tr>
<td>2013</td>
<td>145</td>
<td>145</td>
<td>145</td>
<td>145</td>
<td>145</td>
<td>9238</td>
<td>3411</td>
</tr>
<tr>
<td>2014</td>
<td>146</td>
<td>146</td>
<td>146</td>
<td>146</td>
<td>146</td>
<td>9390</td>
<td>3411</td>
</tr>
<tr>
<td>2015</td>
<td>149</td>
<td>149</td>
<td>149</td>
<td>149</td>
<td>149</td>
<td>9643</td>
<td>3411</td>
</tr>
<tr>
<td>2016</td>
<td>148</td>
<td>148</td>
<td>148</td>
<td>148</td>
<td>148</td>
<td>9628</td>
<td>3411</td>
</tr>
<tr>
<td>2017</td>
<td>149</td>
<td>149</td>
<td>149</td>
<td>149</td>
<td>149</td>
<td>9818</td>
<td>3411</td>
</tr>
</tbody>
</table>

Table 4. Difference between N rates and yields from the North Carolina realistic yield expectations (RYE) database and those achieved in the farmer network. The best N rate is the rate with the highest statistically significant yield averaged across all locations.
The yields did not follow the same trend but varied significantly as N rates increased, so did grower rates but at a much greater rate. Yields were on average 1175 kg ha$^{-1}$ lower than measured. The yield of N averaged the seasonality in grain production per unit N by selecting N rates that produced 10 kg grain kg$^{-1}$ N less than then the agronomic best rate and either Nstd or N-25% rate. The RYE-based PNF$_N$ was tied more closely to differences in yield. The large year-to-year changes in grain production per unit of applied N are likely related to seasonal N availability from the soil system not accounted for in the PNF$_N$ metric. Overall growers managed the seasonality in grain production per unit N by selecting N rates that produced 10 kg grain kg$^{-1}$ N less than then the agronomic best rate but yielded 75 kg ha$^{-1}$ higher.

The N balance (N kg grain kg$^{-1}$ N) calculation is being advanced as an easy to use determinant of N efficiency (McLellan et al., 2018). Based on recent wheat and maize research (Rajkovich et al., 2017), an N balance between 25 and 75 kg N ha$^{-1}$ is necessary to replace mineralized soil organic N in North Carolina soils while avoiding excessive N loss.

In maize, the PNF$_N$ greater than the agronomic best rate and N$_{25\%}$ was statistically similar each year (Table 5). Between years the efficiency of grain production from applied N varied substantially but remained statistically similar to the RYE-based PNF$_N$ in all but the most productive year (2013). As a long-term average, however, the agronomic best PNF$_N$ was 60 kg grain kg$^{-1}$ N, matching that of the RYE database and similar to that reported for new era hybrids by Ciampitti and Vyn (2012) (56.0 ± 13.5 kg grain kg$^{-1}$ N$^{-1}$). Yearly variation in PNF$_N$ in above average yielding years was largely driven by differences in the N rates selected. However, in more moderate and low yielding seasons PNF$_N$ was tied more closely to differences in yield. The large year-to-year changes in grain production per unit of applied N are likely related to seasonal N availability from the soil system not accounted for in the PNF$_N$ metric. Overall growers managed the seasonality in grain production per unit N by selecting N rates that produced 10 kg grain kg$^{-1}$ N less than then the agronomic best rate but yielded 75 kg ha$^{-1}$ higher.

The N balance (N kg grain kg$^{-1}$ N) calculation is being advanced as an easy to use determinant of N efficiency (McLellan et al., 2018). Based on recent wheat and maize research (Rajkovich et al., 2017), an N balance between 25 and 75 kg N ha$^{-1}$ is necessary to replace mineralized soil organic N in North Carolina soils while avoiding excessive N loss.

In wheat, 76% of the trials had an N balance of 75 kg N ha$^{-1}$ or less (Table 6). Of these 60 trials, four had a net negative balance indicating a loss from grain removal alone. The PNF productivity for the 47 growers averaged 40 kg grain kg$^{-1}$ N, considerable more N efficient than the statewide RYE based estimate of 33 kg grain kg$^{-1}$ N (1.8 lb N bushel$^{-1}$) (North Carolina Nutrient Management Workgroup, 2017). Of those trials with an N balance greater than 75 kg N ha$^{-1}$, all but three trials had an N rate greater than 125 kg ha$^{-1}$ and none with a PNF better than 25 kg grain kg$^{-1}$ N. On average, trials with an N balance greater than 75 kg N ha$^{-1}$ applied 32 kg N ha$^{-1}$ more N, yielded 2000 kg grain ha$^{-1}$ less, and were 23 kg grain kg$^{-1}$ N less productive.

In maize, 53% of the trials had an N balance less than 75 kg N ha$^{-1}$, 5% with a net removal of N through harvest (Table 6). The majority of trials (45%) had in an N balance between 25 and 75 kg N ha$^{-1}$. On average, yield accounted for 60% of the variability in the resulting N balance with the year-to-year importance of yield on N balance ranging from 63% in 2013 to 30% in 2015, wet and dry years, respectively. This importance of yield on N balance is observed during years with lower than average yields where more trials are reported with higher N losses. These results support that the majority of growers apply N at a rate adequate to maintain organic N lost through mineralization in most years.

### Table 5. Comparison of average N partial factor productivity (kg grain kg N$^{-1}$) per season for wheat and maize. Realistic yield expectation (RYE) N factor productivity (PFP based) on estimated yields and recommended N rates from RYE data table. Significance reported by year at alpha = 0.10.

<table>
<thead>
<tr>
<th>N Rate</th>
<th>Wheat</th>
<th>Maize</th>
</tr>
</thead>
<tbody>
<tr>
<td>N$_{25%}$</td>
<td>42a†</td>
<td>38a</td>
</tr>
<tr>
<td>N$_{std}$</td>
<td>35a</td>
<td>32ab</td>
</tr>
<tr>
<td>N$_{25%}$</td>
<td>30b</td>
<td>27b</td>
</tr>
<tr>
<td>Agronomic best</td>
<td>39a</td>
<td>35a</td>
</tr>
<tr>
<td>RYE</td>
<td>29b</td>
<td>29b</td>
</tr>
</tbody>
</table>

† Significance of least-squares means at the 0.10 level indicated by different letters.

### Nitrogen Partial Factor Productivity and Nitrogen Balance

In wheat, the PNF$_N$ for the agronomic best N rate, N$_{std}$ rate, and the North Carolina RYE-based rate averaged 37, 33, and 29 kg grain kg$^{-1}$ N, respectively (Table 5). On average, there was no statistical difference in N productivity between the agronomic best rate and either N$_{std}$ or N$_{25\%}$ rate. The RYE-based estimate of N productively however suggested a significantly lower N productivity, 4 to 8 kg of grain per kilogram of N than that measured from the N$_{std}$ rate and the agronomic best rate, respectively. This discrepancy is attributed to older wheat varieties found in the RYE database and their less efficient use of N. It is expected that future updates to the RYE database will result in N productivity values similar to those observed with the agronomic best rate. Overall, the N productivity from the grower standard N rate as measured by PNF$_N$ was within 4 kg per kilogram of N of the agronomic best, an amount equal to that observed in the year-over-year variability.
At the $N_{25\%}$ rate, 50% of trials had an N balance less than 25 kg N ha$^{-1}$, a level at the lower bound of what is proposed as a “safe operating zone” (McLellan et al., 2018; EU-NEP, 2015). Although N balance is being used as a simple metric to assess the impact of changes in farm management on potential N losses to the environment, careful consideration should be taken to assess seasonal variability in yield when changes in management are considered when based on the PNF$_N$ metric.

**Farmer Networks**

Farmer networks are designed to share results, ideas, and perspectives across a network of peers. The networks are used to encourage discussions and facilitate behavioral change based on experimental results and group feedback. In North Carolina, feedback was provided yearly as summarized results so that members could evaluate N selection and performance relative to themselves as well as to others in the network. Despite inviting farmers to working meetings (at either lunch or dinner) and providing them with geospatial yield data, soil test data, and a simple to understand yield analysis, few farmers attended the yearly workshops. Based on analysis of annual N rates over time by individual farmers, we saw no change in behavior from either the farmers or the consultants. In part we believe this is due to most farmers only wanting to participate for 2 to 3 yr and that the results confirmed their expectations. Additionally, many farmer network trials are run with a single primary contact whereas there were five consultants with distinct N rate preferences in this trial. Karlen et al. (2017) learned several lessons regarding farmer networks: (i) these networks are expensive, researchers have less control, and farmers are focused on economics; (ii) farmer networks require long-term infrastructure and therefore need dedicated support staff who must identify willing collaborators, lay out replicated field designs, conduct quality control on the data, provide statistical analysis and interpretation, and provide additional information and support; (iii) a diverse science board is critical; (iv) implementation and results will be slower than expected, and; (v) communications with participants and outside audiences is essential. These lessons capture many of the same challenges and observations in the North Carolina farmer network trials.

**CONCLUSIONS**

As noted by Scharf, many challenges exist in determining a single optimum N rates based on location because yield is impacted by a complex interaction of factors including precipitation, temperature, mineralization, and crop development (Scharf, 2001; Scharf et al., 2005). As such, it is understandable that much of the current N selection process is directed by science as much as the judgment of farmers and experience of agronomic advisors.

The establishment of the North Carolina farmer network provided insights into the regional selection of N rates and in the refinement of current N recommendation practices. With wheat, the majority of growers selected N rates that satisfied N needs. The N selections were similar to RYE recommendations but yields were significantly higher than predicted. With maize most growers could have lowered their N rates without a statistically significant yield penalty. The $N_{25\%}$ rate closely matched that recommended by the RYE database but achieved yields were markedly higher than RYE estimates in all but the most rainfall limiting year. These results support the use of RYE as an N rate decision tool rather than for yield goal prediction in maize. Doppler-based rainfall estimates correspond well to gauged rainfall measurements and explain much of the year-to-year variability observed in yield level across the farmer network. The average yield level in maize was highly related to seasonal rainfall regardless of trends in grower selected N rates. In wetter years the yield response to additional N was lower and more growers could have applied less N. The 2-wk periods after N application in both wheat and maize were significant to grain yield, however the rainfall estimates at individual sites had little effect on the independence of yield observed between sites.

Nitrogen metrics, such as PFP$_N$ and PNB, provide a simple measure of N performance useful for comparing and communicating results, however a record of achieved yields over multiple years is needed to determine if gains in N efficiency result from changes in management and not short-term seasonality or yield. The use of these metrics in refining N rates is hindered by the same factors as those methods that rely on improved approaches to predicting the agronomic optimum N rates before the growing season; the inability to adjust for seasonal factors that influence N response and the uncertainty at the time of fertilization in predicting yield. A retrospective analysis of PFP$_N$ calculated form the agronomic best rates and yields indicated N use efficiencies similar to that from the North Carolina RYE data table in all but the most N unresponsive year.

Overall, results indicate that participants in the in farmer network selected N rates that were very close to the seasonal and locational

### Table 6. The number of trials by year grouped by their net N balance. Trials with a negative balance remove more N through grain harvest than applied.

<table>
<thead>
<tr>
<th>Year</th>
<th>&lt;0</th>
<th>0–25</th>
<th>26–50</th>
<th>51–75</th>
<th>76–100</th>
<th>101–150</th>
<th>150–200</th>
<th>Trials</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013</td>
<td>4</td>
<td>6</td>
<td>5</td>
<td>8</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>26</td>
</tr>
<tr>
<td>2014</td>
<td>0</td>
<td>1</td>
<td>6</td>
<td>6</td>
<td>8</td>
<td>2</td>
<td>0</td>
<td>23</td>
</tr>
<tr>
<td>2015</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td>8</td>
<td>0</td>
<td>18</td>
</tr>
<tr>
<td>2016</td>
<td>0</td>
<td>1</td>
<td>6</td>
<td>3</td>
<td>5</td>
<td>3</td>
<td>1</td>
<td>19</td>
</tr>
<tr>
<td>2017</td>
<td>1</td>
<td>0</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>4</td>
<td>1</td>
<td>14</td>
</tr>
</tbody>
</table>
N needs for wheat; for maize exceeded needs about 40% of the time. The importance of location on achievable yield and seasonality on yield response make pre-season decisions about N selection challenging. It is likely that improved approaches to N rate selection and N efficiency will require in-season adjustments to yield-based N rates that incorporate local management and environmental conditions up to and during the growing season.

ACKNOWLEDGMENTS

The authors are grateful to the Environmental Defense Fund for funding this project. We would also like to thank the crop advisors who worked with us on this project: Billy McLawhorn, Hank Haddock, Chad Doch, and Matt Ipock of McLawhorn Crop Services, Inc.; Daniel Fowler of Fowler Crop Consulting, Inc.; Stan Winslow of Tidewater Agronomics, Inc.; Al Averitt of Protech Advisory Services, Inc.; and Daniel Hedgecock of Vantage South Atlantic. The conclusions are those of the authors and do not necessarily reflect the positions of the funders or advisors.

REFERENCES


Haber, F. 2012. Thermodynamik technischer Gasreaktionen. 1st ed. (In German.) Salzwater Verlag, Paderborn, Germany.


