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Corn yield response to sub-surface banded starter fertilizer in the U.S.: A meta-analysis

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ABSTRACT

Sub-surface fertilizer application at planting (i.e., starter fertilization) is a common practice in U.S. corn (*Zea Mays* L.) production to improve early-season nutrient uptake, nutrient use efficiency, and plant growth, especially under cool and moist spring soil conditions. However, yield increases from starter applications can vary across production systems and environments. Here, we use a meta-analysis approach to quantify and generalize corn yield responses to sub-surface starter fertilizer applications in the U.S. and to understand the management and environmental factors that drive variability in corn yield response across previously published research. This meta-analysis summarizes peer-reviewed research from the U.S. published between 1990 and 2019. The dataset encompasses 474 observations from 23 studies conducted in various locations and includes information regarding management practices used and soil and weather conditions. We calculated effect size as the natural log of the response ratio, with the response ratio determined as corn yield with a starter fertilizer application containing nitrogen (N) and phosphorus (P) or N, P and potassium (K) relative to corn yield without a starter fertilizer application. Additionally, we investigated the impact of potential moderator variables on corn response to sub-surface starter fertilization (e.g. agronomic practices, soil properties, and weather conditions). On average, fertilizer sub-surface applied in the furrow or banded 5 cm to the side and 5 cm below the seed at planting increased corn yield by 5.2 %. Corn response to starter fertilization was consistent across many agronomic and environmental conditions including different tillage systems, previous crops, soil textures, and planting season weather conditions. Yield benefits decreased with increasing soil test P and K levels. Nevertheless, yield increases from starter fertilization occurred with soil test levels up to 500 % and 300 % of the P and K critical levels, respectively. In addition, corn yield benefits from starter fertilization decreased as corn planting density increased and as corn yield level decreased. Overall, this meta-analysis provides support for the use of sub-surface starter fertilizer applications to improve corn yield.

1. Introduction

Sub-surface starter fertilizers containing single nutrients or combinations of nutrients [e.g., nitrogen (N), phosphorus (P), potassium (K)] are routinely applied in bands close to the corn (*Zea mays* L.) seed furrow at planting to improve early-season nutrient uptake, nutrient use efficiency, and plant growth under cool and moist soil conditions (Bermudez and Mallarino, 2004; Wortmann et al., 2006; Kaiser et al., 2016; Rutan and Steinke, 2018). Sub-surface placement of fertilizer at planting provides immediate nutrient access to emerging corn roots, increases the concentration of relatively immobile nutrients (P and K) near the corn rooting zone, stimulates root growth, induces favorable rhizosphere chemical changes, limits volatilization of N, and reduces total nutrient losses, thus improving use efficiency of applied nutrients (Riley and Barber, 1971; Zhang et al., 2000; Lamond and Gordon, 2001; Kaiser et al., 2005). In addition, nutrient placement close to the seed at planting has been shown to increase early-season dry matter production (Kaiser et al., 2005; Kim et al., 2013; Kaiser et al., 2016), plant height (Vetsch and Randall, 2002; Rutan and Steinke, 2018), shorten the period between planting and silking (Bullock et al., 1993; Cromley et al., 2006; Kaiser et al., 2016), and reduce grain moisture at harvest (Bullock et al., 1993; Kaiser et al., 2016).

Sub-surface starter fertilizers may be placed directly in the seed furrow (IF) or 5 cm to the side and 5 cm below the seed (5 × 5). In-

Abbreviations: 5 × 5, banded 5 cm. to the side and 5 cm. below the seed; IF, in-furrow; K, potassium; LRR, natural log of the response ratio; N, nitrogen; P, phosphorus; RR, response ratio; SOM, soil organic matter; STK, soil test potassium; STP, soil test phosphorus

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furrow starter fertilizer placement requires less specialized equipment, allows faster planting, and is less impacted by springtime soil moisture than 5 × 5 placement (Kaiser et al., 2016; Rutan and Steinke, 2018). Relative to no starter, IF fertilizer use increased early-season corn height (Mascagni and Boquet, 1996; Vetsch and Randall, 2002), plant vigor (Rutan and Steinke, 2018), kernel mass, kernel number (Kaiser et al., 2016), biomass accumulation (Bermudez and Mallarino, 2002, 2004), and grain yield (Mascagni and Boquet, 1996; Bermudez and Mallarino, 2002; Vetsch and Randall, 2002). However, careful consideration of N and K application rates and sources is required with IF to avoid seedling ammonia toxicity and/or salt injury, stand reductions, and yield loss (Raun et al., 1986; Niehues et al., 2004; Rehm and Lamb, 2009; Kaiser et al., 2016; Rutan and Steinke, 2018). In comparison to IF starter use, 5 × 5 placed starter allows for greater fertilizer source and rate flexibility, is a more suitable placement method when N rates > 20 kg N ha^{-1} are desired and allows for a greater supply of early-season N availability until in-season sidedress N applications (Niehues et al., 2004; Rutan and Steinke, 2018). In Missouri and Wisconsin, 5 × 5 placed starter fertilizer increased corn grain yield by 9.6 and 5%, respectively compared to no starter (Scharf, 1999; Wolkowsi, 2000).

Previous literature has attributed variation in corn yield responses to starter fertilization to management and environmental factors including: corn hybrid planted (Gordon et al., 1997; Gordon and Pierzynski, 2006), tillage system (Mengel et al., 1988; Kaiser et al., 2005), starter nutrient composition (Scharf, 1999; Bermudez and Mallarino, 2003; Roth et al., 2006), starter placement (Rehm and Lamb, 2009; Rutan and Steinke, 2018), nutrient rates used (Niehues et al., 2004; Rehm and Lamb, 2009), plant density (Li et al., 2018), soil moisture (Wortmann et al., 2006; Kaiser et al., 2016; Rutan and Steinke, 2018), soil temperature (Kaiser et al., 2016), soil texture (Rehm and Lamb, 2009; Kaiser and Rubin, 2013), and soil test P and K levels (Roth et al., 2006; Wortmann et al., 2006). However, the effects of these factors on corn yield response to starter fertilization have been highly variable. For example, Mengel et al. (1988); Wolkowsi (2000), and Vyn and Janovicek (2001) observed greater corn yield response to starter fertilization under no-till than conventional till, whereas Vetsch and Randall (2002) and Bermudez and Mallarino (2004) observed similar corn responses to starter fertilization across multiple tillage systems. In addition, Ritchie et al. (1996) showed that 5 × 5 starter fertilizer placement more consistently increased no-till corn grain yield than IF, whereas Riedell et al. (2000) and Wortmann et al. (2006) found no difference in the effects of 5 × 5 and IF placement on corn yield.

Because starter fertilizers typically contain two or more nutrients, nutrient-specific reasons for corn grain yield increases are often difficult to interpret (Kaiser et al., 2005; Mallarino et al., 2011). Yield increases in response to starter fertilization may reflect the additive effects of satisfying individual nutrient limitations or the synergistic effects of nutrients contained in the fertilizer enhancing plant growth. Examples of synergistic effects include: i) starter N and P causing root proliferation, which leads to more effective use of K by the crop (Mallarino et al., 2011) and ii) N applied in the ammonium form causing acidification, which increases P uptake by young plants (Riley and Barber, 1971). Larger yield responses tend to be observed on soils testing low in P and K, yet positive responses have been observed when soil test values are above the critical soil test level, which is the soil test value above which the nutrient does not limit yield (Bermudez and Mallarino, 2002; Kaiser et al., 2005; Wortmann et al., 2006; Mallarino et al., 2011). A positive response to starter fertilization when soil test P (STP) and soil test K (STK) are above critical levels may reflect localized deficiencies of P or K in fields where soil test levels are sufficient on average, or an inadequate supply of N in the root zone (Touchton and Karim, 1986; Rehm et al., 1988; Scharf, 1999).

Due to the current popularity of sub-surface starter fertilizer use in the U.S., it is important to understand and generalize the corn yield response under a wide spectrum of conditions and determine the primary factors driving variation in yield responses. To our knowledge, there have been no recent attempts to review and quantify corn yield response to sub-surface starter fertilizer applications using a meta-analysis approach in the U.S. A meta-analysis can help identify specific data patterns only when data across a broad set of agronomic conditions and corn production systems are combined and analyzed within an environmental and agronomic context (Fernandez et al., 2019). The objectives of this meta-analysis were to integrate and synthesize previously published literature regarding corn response to sub-surface starter fertilizer to: (i) develop an estimate of corn yield response to starter fertilizer across multiple management and environmental conditions, (ii) determine which starter fertilizer placement (IF or 5 × 5) provides greater grain yield responses across a variety of management and environmental factors, and (iii) determine the effect of potential moderator variables on the magnitude of starter fertilizer response.

2. Materials and methods

2.1. Article selection

Corn yield response to starter fertilizer application was estimated by a systematic review of peer-reviewed literature. A literature search was performed using the literature databases Google Scholar (Google Inc., Mountain View, CA) and Web of Science (Thomson Reuters, New York, NY) with Boolean expressions: “corn yield *and* starter fertilizer *or* in-furrow fertilizer”. Additional studies were found within reference section of publications produced from this search. The literature search was limited to peer-reviewed journal articles that included in-field replication, randomization, and were published in the U.S. from 1990 through 2019. The following criteria were required for studies to be included in this meta-analysis:

- Grain yield data for corn that received a sub-surface starter fertilizer application and corn that did not receive a sub-surface starter fertilizer application, with other management practices (e.g., primary N fertilization timing, broadcast P and K) held constant between the starter and no starter treatments.
- Starter fertilizer sub-surface banded as a 5 × 5 or IF at planting.
- Grain yield data reported across more than one year or location.
- Treatment means and sample sizes reported for each comparison.

Our database was populated with a total of 474 individual observations across 23 published research trials that met our proposed inclusion criteria (Supplementary Table S1). Treatment means, sample size, and measures of variability [standard deviation, coefficient of variation (CV), or least significant difference (LSD)] were recorded for each observation. The response variable used in the meta-analysis was corn grain yield (Mg ha^{-1}). An observation was considered an individual starter/no-starter comparison. Depending on trial layouts in the database, a starter fertilizer treatment in combination with another factor provided multiple observations for a single study (Marcillo and Miguez, 2017). For example, a study including starter fertilizer and corn hybrid combined in a factorial arrangement resulted in a separate observation for each hybrid calculated at each starter treatment.

Additional factors were taken from the studies chosen and included in the database due to their potential to moderate starter fertilizer impacts on corn grain yield. Potential moderator variables included: starter placement, primary N fertilization timing, previous crop, tillage system, starter nutrient composition, soil texture, SOM level, planting month temperature, planting month precipitation, soil test P and K, plant population, and yield level (Table 1). We acknowledge the use of starter fertilizer applications that are not 5 × 5 or IF (e.g. 5 × 0) and starter fertilizers that contain applications of single nutrients, yet due to the limited published observations and comparisons regarding these factors, we elected to exclude them from our analysis. Soil texture was categorized into fine (clay loam, silty clay loam), medium (silt loam, loam), and coarse (sandy loam) based on specific soil series presented.

Table 1
Moderator variables examined in the meta-analysis of corn yield response to starter fertilizer application.

Moderator variable	Description of moderator variable levels
Starter Placement (n = 474)	In-furrow (IF), 5 × 5 cm. sub-surface band (5 × 5)
Primary N Fertilization Timing[†] (n = 317)	Planting (at planting or before), sidedress (V4-V8 growth stage)
Previous Crop (n = 282) [‡]	Non-legume (corn, cotton, sorghum, wheat), legume (soybean)
Tillage System (n = 274)	Conventional, no-till
Starter Nutrient Composition (n = 474)	Nitrogen (N)-phosphorus (P), N–P-potassium (K).
Soil Texture (n = 374)	Fine (clay loam, silty clay loam), medium (silt loam, loam), coarse (sandy loam)
Soil Organic Matter Level[§] (n = 214)	Low ($0-26$ g kg^{-1}), medium ($27-53$ g kg^{-1}), high ($54-80$ g kg^{-1})
Planting Month Temperature[¶] (n = 177)	Cool (< 15 °C), warm (> 15 °C)
Planting Month Precipitation[¶] (n = 143)	Dry (< 129 mm), wet (> 129 mm)
Soil Test Phosphorus (STP)[#] (n = 286)	Percent change from state-specific critical STP value.
Soil Test Potassium (STK)[#] (n = 234)	Percent change from state-specific critical STK value.
Plant Population (n = 246)	Individual study corn plant population rate (seeds ha^{-1})
Grain Yield (n = 474)	Average corn grain yield (Mg ha^{-1}) across starter treatments for each study site-year

[†] Primary N fertilization timing refers to the time when the majority of N fertilizer was applied, supplementing the N fertilizer applied as starter.
[‡] Cotton (*Gossypium hirsutum* L.), sorghum (*Sorghum bicolor* L.), wheat (*Triticum aestivum* L.), soybean (*Glycine Max* L. Merr.).
[§] Soil organic matter values for the dataset ranged from 3 to 80 g kg^{-1}, therefore values were classified into three equal-range groups of low ($0-26$ g kg^{-1}), medium ($27-53$ g kg^{-1}), and high ($54-80$ g kg^{-1}).
[¶] Mean planting month temperature (15 °C) and precipitation (129 mm) values were calculated from the dataset and temperature and precipitation values were grouped by cool and warm, or wet and dry, respectively, based on whether values were above or below the dataset mean planting month temperature and planting month precipitation.
[#] Soil test phosphorus and potassium analyzed as continuous variables with each observation converted to the percent change from site-specific critical P and K levels derived from state-specific university nutrient management guidelines to account for different in-state recommendation calculations and extraction methods used (Bray-P1, Mehlich-III, Olson-P, etc.).

To evaluate starter fertilizer effects in relatively high and low temperature and rainfall conditions, we first calculated a mean planting month temperature (15 °C) and precipitation (129 mm) across all observations in the dataset. Then, we classified each observation as cool or warm and as wet or dry based on whether the temperature and rainfall values for that observation were above or below the mean values for the entire dataset.

2.2. Meta-analysis

The dependent variable that indicates corn yield response to starter fertilization was quantified by first calculating the response ratio (RR) as an effect size (Hedges et al., 1999):

$$RR = \left(\frac{\bar{x}_{starter}}{\bar{x}_{control}}\right)$$

where $\bar{x}_{starter}$ and $\bar{x}_{control}$ are the reported means for the starter and no starter treatments, respectively, for each observation. After calculating the RR, the natural log of each RR (LRR) was calculated to normalize the data set.

The sampling variance associated with each LRR was estimated using the equation below (Hedges et al., 1999):

$$v_i = \frac{SD_{starter}{}^2}{n_{starter} \times \bar{x}_{starter}{}^2} + \frac{SD_{control}{}^2}{n_{control} \times \bar{x}_{control}{}^2}$$

where yield means ($\bar{x}$), standard deviations (SD), and sample sizes (n) for both the starter fertilizer and control treatments for a given case were used. Variability measurements other than standard deviations (e.g. CV, LSD) reported in studies were used to calculate their respective standard deviations. For example, if a CV was reported for corn grain yield, this was multiplied by the mean corn grain yield of the same treatment to obtain the standard deviation. Additionally, studies reporting LSD values of the response variable were converted to standard errors using the following equation (Rosenberg et al., 2004):

$$SE = \frac{LSD}{t_{(0.975,n)}\sqrt{2bn}}$$

where t corresponds to the t test value, n is the number of samples, and b is the number of blocks or treatment replications. To obtain the standard deviation, standard errors were multiplied by the square root of the sample size. Most studies in our meta-analysis (> 70 %) reported measures of variability; however, certain studies did not contain any measures of variability. Therefore, the average CV was computed for the corn grain yield of other studies in the database and the missing standard deviations were estimated by multiplying the average CV by the respective means (Bai et al., 2013; Thapa et al., 2018).

We evaluated heterogeneity in the effect of starter fertilization on corn grain yield among observations in two ways. First, we calculated a Q statistic to test whether significant heterogeneity was present (Hedges et al., 1999). The Q-statistic follows a chi-square distribution with (n-1) degrees of freedom, therefore if the Q-statistic estimate produces a p-value less than 0.05, it can be concluded that starter fertilizer responses differ among observations (Hedges et al., 1999). In addition, the I-square (I^2) index was used to quantify the heterogeneity in our data set (Higgins and Thompson, 2002). The I-square value was calculated through the following equation (Higgins and Thompson, 2002):

$$I^2 = \frac{Q - (n-1)}{Q} \times 100$$

where Q is the total variance, and (n-1) is the degrees of freedom. I-square values exceeding 50 % suggest significant heterogeneity, which justifies the inclusion of moderator variables (e.g. starter placement, tillage, preceding crop, etc.) to help explain variance among studies (Higgins and Thompson, 2002).

Estimation of sampling variance, heterogeneity analysis, calculation of mean LRRs and their corresponding 95 % confidence intervals, and meta-regression of continuous variables were conducted using functions in the metafor R-package, version 1.9–4 (Viechtbauer, 2017). We fit a mixed effects model using the rma.mv function, which weights LRRs based on their sampling variances. Individual study identification was categorized and included in the model as a random factor. The overall effect of starter fertilization on corn yield relative to no starter was tested using this model at α = 0.05. We also fit mixed-effects models that each included a moderator variable (e.g., previous crop, tillage, etc.) as a fixed effect. Mean LRRs at each level of a given moderator variable were considered significantly different from zero (i.e., starter fertilization significantly impacted yield relative to no starter) if their 95 % confidence intervals (CI) did not include 0 and significantly different from each other if their 95 % CIs did not overlap

(Wortman et al., 2017; Schmidt and Gaudin, 2018; Thapa et al., 2018). We also performed subgroup analysis to understand the conditions in which specific moderator effects were most pronounced. Subgroup analysis involved fitting mixed-effects models for each level of each moderator of interest. For example, to determine the impact of starter placement within different primary N application timings, data were subset into categories of primary N application timings (i.e., planting and sidedress) and mixed-effect models that included the moderator variable starter placement as a fixed effect were fit within each data subset.

To explore the quantitative relationship between corn yield response to starter fertilizer at different continuous variables (STP, STK, plant population, yield level) a weighted quadratic meta-regression model was used to regress the dependent variable LRR against the continuous variables chosen. Mean corn grain yield (Mg ha^{-1}) values across starter treatments for each study site-year were used in the yield level regression analysis. To account for different state-specific university soil nutrient management recommendations and soil test extraction methods, we compiled state critical STP and STK values (STP and STK values at which no additional P or K fertilizer is required to maximize corn grain yield) and calculated the percent difference between an individual observation's STP or STK value and the state-specific nutrient management guideline critical values. Many state-specific recommendations require additional information to determine the critical STP and STK level (e.g. crop expected yield, soil type, soil cation exchange capacity, etc.), therefore we used all possible data from published studies to determine critical values or used an average value within the suggested range of critical STP or STK values presented by state-specific nutrient management guidelines. Only observations with a starter containing K (N-P -K) were used in the STK regression analysis.

Sensitivity analysis was performed by calculating the weighted mean LRR with each study removed one-at-a-time from the data set (Supplemental Fig. S1). Removing any individual study did not change the statistical significance of the mean effect estimate, as illustrated by no error bars overlapping with zero when a study was removed. In addition, removing individual studies that did not report measures of variability and contained an estimated average CV did not change mean effect estimates, thus justifying their inclusion and confirming the robust nature of our data (Thapa et al., 2018). To investigate publication bias we used a funnel plot of effect size against the inverse of the standard error (Supplemental Fig. S2). A symmetrical funnel shape in the scattering of individual observations was observed, suggesting that studies did not omit non-significant results, which would result in publication bias (Anzures-Cabrera and Higgins, 2010).

3. Results

3.1. Database description

The database included studies with both IF (n = 156) and 5 × 5 (n = 318) starter fertilizer applications with respective mean N, P, and K starter applied rates of 8.2, 9.3, and 4.3 kg ha^{-1} for IF and 23, 24, and 17 kg ha^{-1} for 5 × 5 (Fig. 1). Mean N, P, and K starter rates for observations following a non-legume were 38.1, 21.8, and 12.6 kg ha^{-1}, respectively and following a legume were 12.7, 17.7, and 10.5 kg ha^{-1}, respectively. Additionally, mean N, P, and K starter rates for no-till observations were 28.8, 24.1, and 8.9 kg ha^{-1}, respectively and for conventional tillage observations were 14.1, 11.4, and 14.5 kg ha^{-1}, respectively (data not shown). Across 317 starter comparisons with associated data on primary N fertilization timing, a total of 244 observations had primary N applied (130–224 kg N ha^{-1}) at-planting or before, compared to only 73 observations that had primary N applied (85–180 kg N ha^{-1}) as in-season sidedress (i.e., corn growth stage V4-V8) (Fig. 2). Total N rates for studies following a non-legume averaged 183 kg N ha^{-1} compared with 163 kg N ha^{-1} for studies following a legume, yet similar total N rates were applied across tillage systems (166 and 167 kg N ha^{-1} for no-till and conventionally tilled systems, respectively) (data not shown).

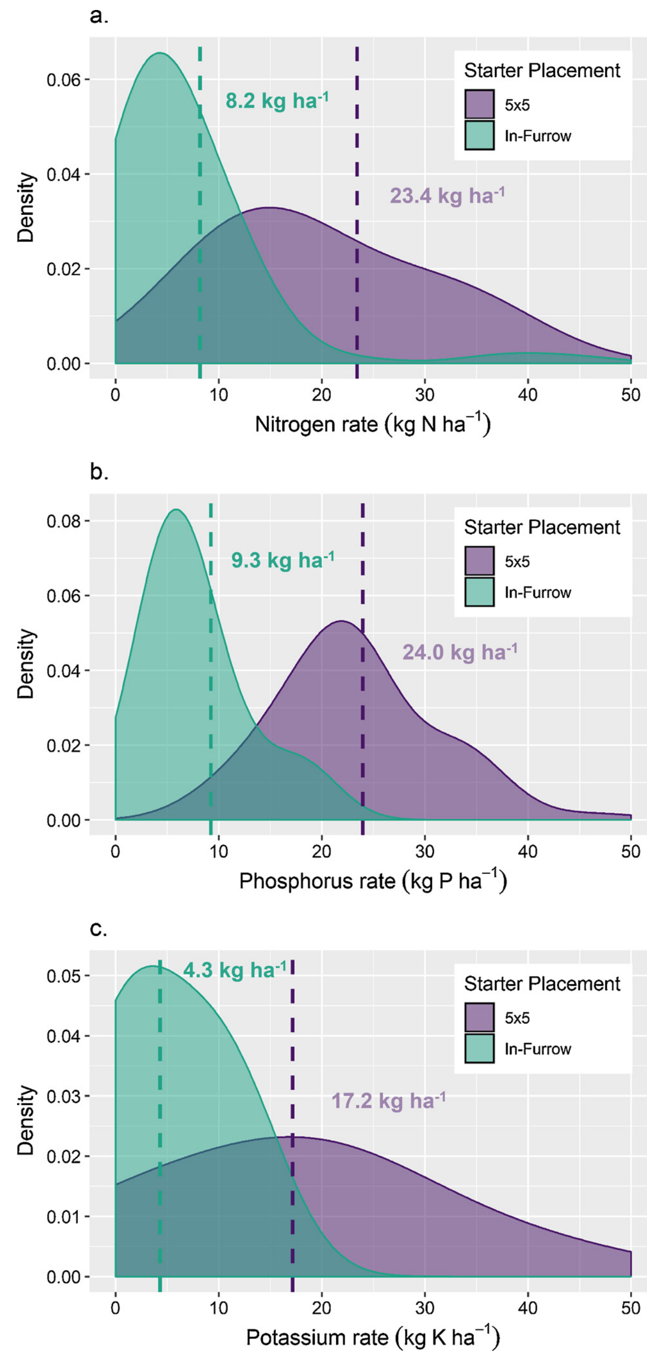

Fig. 1. Description of starter fertilizer nutrient rates across the database. A) starter fertilizer N rate density distribution plot, B) starter fertilizer P rate density distribution plot, and C) starter fertilizer K rate density distribution plot. Dashed vertical lines and values represent the mean nutrient (N, P, K) rates applied.

Database grain yields ranged widely (2.2-15.3 Mg ha^{-1}), which can be attributed to the diversity of cropping systems (soil properties, precipitation, topography, hybrids used, etc.) included in the analysis. Results encompassed a total of nine states across the U.S. with the majority of observations present in the Midwestern Corn Belt (i.e. IA, MN, WI) (Supplemental Table S1). Dominant soil types include silt loam and silty clay loam with SOM levels that ranged from 3 to 80 g kg^{-1}. Dominant cropping systems were both no-till and conventionally tilled corn following soybean. Planting month temperature and precipitation

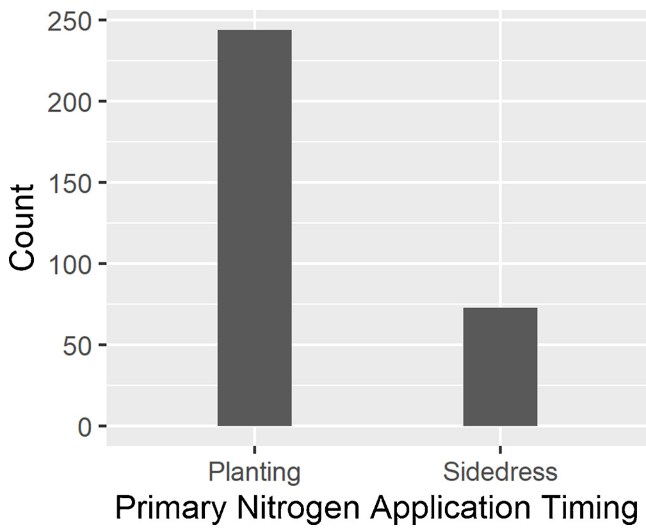

Fig. 2. Database total count of observations with planting (at-plant or pre-plant) and sidedress (V4-V8 growth stage) primary N fertilization timings.

ranged from 5.8 to 21.1 °C and 33–404 mm, respectively, with the majority of corn studies planted from late April to early May.

3.2. General effects of starter fertilization on corn grain yield

Averaged across all individual observations, starter fertilization significantly increased corn grain yield by 5.2 % (Fig. 3), with percentage change due to starter fertilization ranging from -17 to 37 %. Of the 474 individual comparisons examined, 352 (74 %) had a positive effect of starter fertilizer application on corn yield compared to a no starter fertilizer control. Mean grain yields for the starter fertilizer treatment and no starter fertilizer control were 9.6 and 9.2 Mg ha^{-1}, respectively. Analysis of heterogeneity conducted for the entire dataset (Q = 8607, I^2 = 95 %, df = 473, P < 0.0001) indicated significant heterogeneity among the pooled observations, justifying the incorporation of moderator variables to further examine the impact of various agronomic and environmental factors on the magnitude of corn yield increases to starter fertilization.

3.3. Impacts of management and environmental factors on corn response to starter fertilization

Despite higher applied nutrient rates for the 5 × 5 starter placement (Fig. 1), IF and 5 × 5 produced similar corn yield responses considering the entire data set (Fig. 3). However, when primary N fertilizer application was delayed until sidedress, the 5 × 5 starter significantly increased corn yield by 8.9 % relative to no starter, while IF starter had no significant effect on corn yield (Fig. 3). Corn yield increase to starter fertilization did not differ between corn following a legume crop (soybean) and corn following a non-legume crop (corn, cotton, sorghum, or wheat) or between conventional and no-till management systems (Fig. 3). Corn yield increase in response to starter fertilizer application did not significantly differ between starters containing N-P and those containing N-P -K (Fig. 3). Corn yield increase to starter fertilization also did not statistically differ across soil textures, SOM levels, planting month temperatures, and planting month precipitation amounts (Fig. 3).

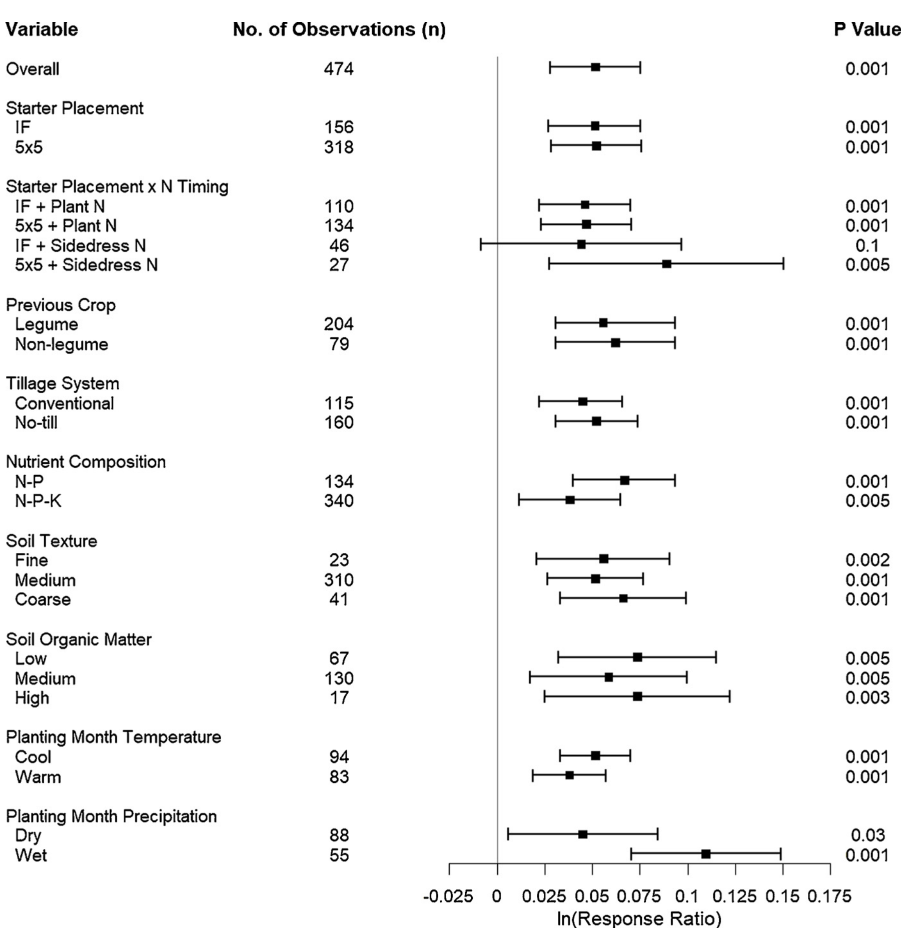

Fig. 3. Mean natural log of the response ratio (LRR) (ln [corn yield with starter fertilizer/corn yield without starter fertilizer]) across the overall dataset and as impacted by moderator variables. Error bars represent 95 % confidence intervals and overlapping confidence intervals represent a non-significant (P > *0.05*) difference in the means. Significant p-values (≤ 0.05) on the right indicate a significant corn yield increase due to starter fertilization. Number of observations (n) indicate total number of comparisons contributing to the mean LRR. Moderator variables include: starter placement (IF = in-furrow; 5 × 5 = sub-surface band placed 5 cm next to and 5 cm below the seed), starter placement by primary N application timing (Plant N = N applied at planting or before; Sidedress N = N applied at the V4 corn growth stage and later), previous crop (Legume = soybean; Non-legume = corn, cotton, sorghum, wheat), tillage, starter nutrient composition, soil texture (Fine = clay loam, silty clay loam; Medium = silt loam, loam; Coarse = sandy loam), soil organic matter level (Low = 0-26 g kg^{-1}; Medium = 27-53 g kg^{-1}; High = 54-80 g kg^{-1}), planting month temperature (Cool = < 15 °C; Warm = > 15 °C), and planting month precipitation (Dry = < 129 mm; Wet = > 129 mm).

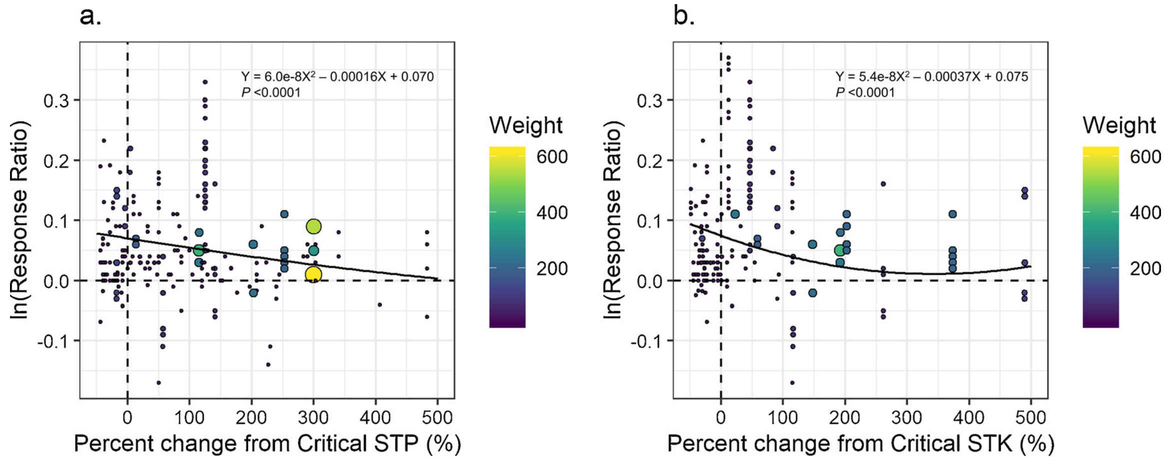

Fig. 4. Relationship between the natural log of the response ratio (LRR; yield of corn containing a starter fertilizer/yield of corn not containing a starter fertilizer) and the percent change from state-specific a) critical soil test phosphorus (STP) level and b) critical soil test potassium (STK) level. Horizontal and vertical dashed lines indicate where the LRR and percent change from the critical soil test level equal zero, respectively. The size and color of individual data points are proportional to the calculated weight of the observation. For visual clarity, the x-axis of Fig. 4a was truncated to include a range that encompasses the majority of observations; the full response is shown in Supplemental Figure S3.

3.4. Impacts of soil test levels on corn response to starter fertilization

The natural log of the response ratio significantly decreased and approached an LRR of 0 as the percent change from the critical STP and STK value increased (Fig. 4). However, yield increases due to starter (LRR > 0) were observed at soil test levels up to approximately 500 % and 300 % of the P and K critical levels, respectively. When percentage change from critical STP was negative, only 5% of observations produced a negative yield response, whereas when percentage change from critical STP was positive, 15 % of observations produced a negative yield response. When percentage change from critical STK was negative, only 2% of observations produced a negative yield response, whereas when percentage change from the critical STK was positive, 10 % of observations produced a negative yield response.

3.5. Impacts of plant population and yield level on corn response to starter fertilization

The natural log of the response ratio decreased as corn plant population increased (Fig. 5a) and increased as corn yield level increased (Fig. 5b). The relationship between the natural log of the response ratio and plant population showed that starter fertilization had a negative effect on average when corn population exceeded ~86,000 plants ha^{-1}.

4. Discussion

This meta-analysis represents the first quantitative synthesis of sub-surface starter fertilization effects on corn in the U.S. including both agronomic and environmental factors and provides strong evidence for the positive impact of a sub-surface starter fertilizer application on corn grain yield. However, as illustrated by the high level of heterogeneity (I^2 = 95 %) produced in this analysis, corn yield responses to starter fertilizer applications are likely dictated by many complex interactions of site-specific factors that include soil properties, weather, genotype, and management, of which only a select few could be included in this analysis. Yet, the meta-analysis approach allows us to generalize these variable, site-specific responses of corn yield to sub-surface starter fertilizer applications across a wide-range of environmental conditions. Our results align with a previous meta-analysis on subsurface fertilizer placement by Nkebiwe et al. (2016), which showed that placement of fertilizer close to the seed (surface-band, IF, sub-surface deep banding, etc.) significantly increased corn yield by an average of 4.5 %. However, the impacts of producer management techniques (e.g. crop rotation, primary N fertilizer timing, critical soil test levels) and specific environmental conditions (e.g. soil texture, SOM, air temperature, precipitation) on corn starter fertilizer response were not addressed in their analysis.

Although the nutrient application rates were on average 3-fold greater with 5 × 5 placement than IF placement, corn yield response to starter fertilization was similar for both placement methods in our study. Higher nutrient application rates with 5 × 5 starter applications are often associated with greater yield benefits relative to IF in field experiments (Lamond and Gordon, 2001; Bermudez and Mallarino, 2002). Because only four of the 23 studies that we analyzed included both IF and 5 × 5 treatments, we did not attempt to compare corn

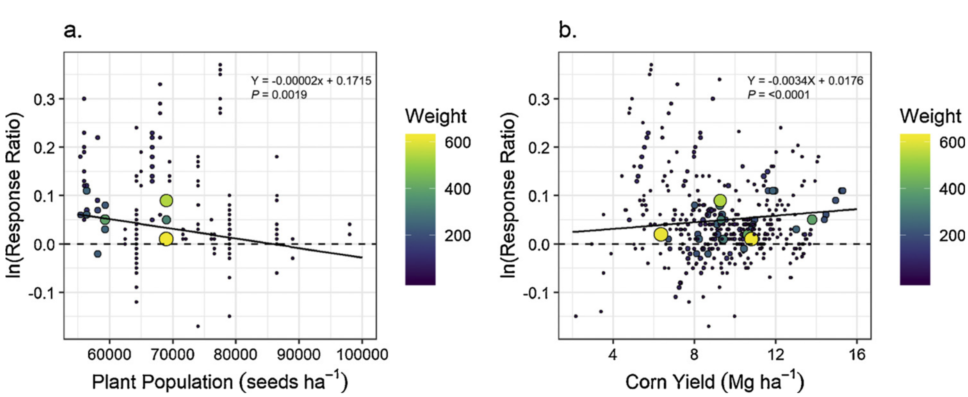

Fig. 5. Relationship between the natural log of the response ratio (LRR; yield of corn containing a starter fertilizer/yield of corn not containing a starter fertilizer) and a) corn plant population (seeds ha^{-1}) and b) corn yield level (Mg ha^{-1}). Horizontal dashed lines indicate where the LRR equals zero. The size and color of individual data points are proportional to the calculated weight of the observation.

yields for different starter placement treatments within the same environment. A more direct comparison of starter application methods, for example by calculating a response ratio of corn yield with 5 × 5 relative to corn yield with IF, may reveal a stronger placement effect but would require additional studies.

The majority of trials examined in our study had ample N at planting (Fig. 2), which likely diminished the benefit of higher N rates associated with the 5 × 5 placement method (Mascagni and Boquet, 1996; Bermudez and Mallarino, 2002). To further examine the non-significant effect of placement on corn yield response to starter fertilization, we investigated the effect of starter placement when primary N was applied at planting or before vs. as a sidedress application. Although not significantly different from each other, which was perhaps due to a low number of primary N sidedress observations, a 5 × 5 starter application significantly ($P < 0.05$) increased corn yield when primary N was delayed until sidedress compared to a non-significant ($P > 0.05$) yield increase for an IF starter. This result corroborates previous research showing that a 5 × 5 starter can provide a better buffer against early-season N stress than IF due to the higher N rate applied, resulting in greater producer flexibility in N application timing (Bermudez and Mallarino, 2002; Rutan and Steinke, 2018). We conclude that both IF and 5 × 5 starters increase corn yield; however, yield responses may be greater for a 5 × 5 starter when primary N application timing is delayed because more N can be applied as 5 × 5 than as IF starter. Our results highlight that further research is needed to understand corn yield response differences between IF and 5 × 5 starter applications across different N fertilizer application timings.

Corn yield response to starter fertilization did not differ between corn following a legume crop (soybean) and corn following a non-legume crop (corn, cotton, sorghum, or wheat). We expected a smaller corn yield response to starter fertilization following a legume crop due to faster N release from legume residues resulting in higher early-season plant-available N than from non-legume residues (Stranger and Lauer, 2008; Gentry et al., 2013). However, the majority of studies used in our analysis applied primary N at planting or before (Fig. 2), which may have diminished the effect of previous crop residue on plant-available N supply. In addition, at-plant or pre-plant total N and starter N rates for studies were 12 % and 127 % higher, respectively for corn succeeding a non-legume crop compared to corn succeeding a legume crop (Supplemental Table S1). Corn producers are often advised to apply higher rates of N fertilizer for corn following a non-legume (Stranger and Lauer, 2008), which may negate differences in early-season N availability caused by the previous crop and overshadow differences in yield benefits from starter fertilizer application across rotations.

Corn yield response to starter fertilization did not differ between conventional and no-till management systems (Fig. 3). These results contrast research by both Mengel (1992) and Wolkowsi (2000) who reported multiple significant corn yield increases to starter fertilization at locations under no-till management and minimal or no significant corn yield increases to starter fertilization at tilled locations. Starter fertilizer use has been promoted for no-till management systems to ameliorate the negative effects of surface residues on corn emergence, root growth, and nutrient supply (Johnson and Lowery, 1985; Mengel, 1992; Kolberg et al., 1999; Lamond et al., 2000; Wolkowsi, 2000; Niehues et al., 2004). The presence of a residue and mulch cover in a no-till soil system can significantly lower at-plant soil temperature and decrease the rate of nutrient mineralization from SOM (Bonan and Van Cleve, 1992). The non-significant effect of tillage on corn yield response to starter fertilization in our study suggests that tillage-related differences in soil conditions (e.g., soil moisture, temperature) may not be great enough to warrant adjustments to fertilizer management, at least under the management and environmental conditions captured in our analysis. However, we note that the non-significant effect of tillage on starter fertilizer response may be due to the majority of studies applying adequate N fertilizer at or prior to corn planting and the higher starter N and P rates associated with the no-till trials.

Corn yield increase due to starter fertilization was similar among a wide range of soil textures, SOM levels, planting month temperatures, and planting month rainfall amounts found in the U.S. (Fig. 3). Our meta-analysis contradicts the commonly-held belief that starter fertilization is more beneficial in soils with low SOM and under cool and wet planting conditions, which are generally associated with restricted root growth and low nutrient availability (Wolkowski, 1990). We note that the starter fertilization LRR was numerically (though not statistically) greater under high precipitation conditions (Fig. 3), and that a wider geographical spread of study locations and data on soil temperature and moisture conditions may reveal more striking effects of environmental moderators.

The number of observations for each starter fertilizer formulation reveals that, at least in research studies, the vast majority of starter fertilizers contain N with either P, or P and K included. The high frequency of starter fertilizers containing combinations of multiple nutrients is well-justified based on the consistent positive effects of these starter compositions on corn yield as illustrated in the results (Fig. 3). In addition, liquid-based applications of single nutrients (e.g. K) are often more expensive due to product availability and formulations required to limit seedling injury (Mallarino et al., 2011).

Meta-regression results for both STP and STK levels demonstrated that as STP and STK levels increase beyond recommended soil test critical levels, the magnitude and frequency of corn yield response to starter fertilizer containing P or K decreases. However, our results also showed that a significant portion of positive yield responses were produced at above critical STP and STK values, suggesting starter fertilizer has the potential to improve corn yield even when soil test results don't warrant a fertilizer application. Our results corroborate previous studies that show multiple-nutrient starter responses on both above- and below-critical STP and STK soils, but larger responses in below-critical STP and STK soils (Bermudez and Mallarino, 2002; Kaiser et al., 2005; Wortmann et al., 2006; Mallarino et al., 2011). The greater starter fertilization response on below-critical STP and STK soils than above-critical STP and STK soils likely reflects the potential alleviation of all three nutrient deficiencies on below-critical soils and alleviation of only N deficiency or localized P and K deficiencies on above-critical soils (Bermudez and Mallarino, 2002; Kaiser et al., 2005; Wortmann et al., 2006).

Meta-regression results for corn plant population indicate that the benefit of starter fertilization decreases with increasing plant population. Our results support recent research showing that localized nutrient applications near the root zone (e.g., starter fertilizer) at high corn plant densities may cause yield reduction relative to broadcast fertilizer applications due to excessive root proliferation and competition for soil nutrients (Li et al., 2018). Contrary to the results for corn plant population, the meta-regression results for corn yield level indicate that the benefit of starter fertilization increases with increasing yield level. As corn yield potential increases, corn nutrient uptake requirements also increase (Setiyono et al., 2010). A greater response to starter fertilizer application in high- than low-yielding environments may reflect the greater crop nutrient demand and reduced risk of other resource limitations in high-yielding environments. Taken together, these findings generate uncertainty about the future value of starter fertilization if both plant populations and yields continue to increase in the U.S.

5. Conclusions

To our knowledge, this is the first attempt to summarize and quantify corn yield response to starter fertilization in the U.S. and encompass different producer management techniques, environmental conditions, and yield levels using meta-analytical methods. Our meta-analysis demonstrated that starter fertilization of corn increased grain yield by an average of 5.2 % regardless of placement across a combination of various environments and management practices in the U.S. We found that as STP and STK levels decreased, corn yield response to starter applications significantly increased, suggesting a greater response to P and K starters at low STP and STK levels. Starter fertilizer applications may also provide corn yield benefits when soil test levels do not warrant a fertilizer application, which suggests potential improved root exploitation of soil nutrient pools and alleviation of early-season localized nutrient deficiencies with starter nutrient placement even when soil nutrient levels are on average adequate. Additionally, our results show that as corn plant population and yield level is increased, yield increases in response to starter fertilization are decreased and increased, respectively. Overall, we provide evidence for the use of sub-surface starter fertilizer applications to improve corn yield under various agronomic and environmental conditions.

CRediT authorship contribution statement

Daniel J. Quinn: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Chad D. Lee:** Writing - review & editing, Supervision, Project administration, Funding acquisition. **Hanna J. Poffenbarger:** Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing - review & editing, Visualization, Supervision, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.fcr.2020.107834.

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