Field Crops Research 215 (2018) 74–82

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Soybean response to nitrogen application across the United States: A synthesis-analysis

Spyridon Mourtzinis[a,*], Gurpreet Kaur[b], John M. Orlowski[b], Charles A. Shapiro[c], Chad D. Lee[d], Charles Wortmann[c], David Holshouser[e], Emerson D. Nafziger[f], Hans Kandel[g], Jason Niekamp[f], William J. Ross[h], Josh Lofton[i], Joshua Vonk[f], Kraig L. Roozeboom[j], Kurt D. Thelen[k], Laura E. Lindsey[l], Michael Staton[m], Seth L. Naeve[n], Shaun N. Casteel[o], William J. Wiebold[p], Shawn P. Conley[a]

[a] Department of Agronomy, University of Wisconsin-Madison, Madison, WI 53706, USA
[b] Delta Research and Extension Center, Mississippi State University, Stoneville, MS 38776, USA
[c] Department of Agronomy and Horticulture, University of Nebraska-Lincoln, Lincoln, NE 68583-0915, USA
[d] Department of Plant and Soil Sciences, University of Kentucky, Lexington, KY 40546-0312, USA
[e] Department of Crop and Soil Environmental Sciences, Virginia Tech, Blacksburg, VA 24061, USA
[f] Department of Crop Sciences, University of Illinois, Urbana, IL 61801, USA
[g] Department of Plant Sciences, North Dakota State University, Fargo, ND 58108-6050, USA
[h] Department of Crop, Soil, and Environmental Sciences, University of Arkansas System Division of Agriculture, Little Rock, AR 72204, USA
[i] Department of Plant and Soil Sciences, Oklahoma State University, Stillwater, OK 74074, USA
[j] Department of Agronomy, Kansas State University, Manhattan, KS 66506-0110, USA
[k] Department of Plant, Soil & Microbial Sciences, Michigan State University, East Lansing, MI 48824, USA
[l] Department of Horticulture and Crop Science, The Ohio State University, Columbus, OH 43210, USA
[m] Michigan State University Extension, Allegan, MI 49010, USA
[n] Department of Agronomy and Plant Genetics, University of Minnesota, St. Paul, MN 55108, USA
[o] Department of Agronomy, Purdue University, West Lafayette, IN 47907, USA
[p] Division of Plant Sciences, University of Missouri, Columbia, MO 65211, USA

ARTICLE INFO

Keywords:
Soybean
Nitrogen
Hierarchical model
Regression tree

ABSTRACT

The effects of supplemental nitrogen (N) on soybean [*Glycine max* (L.) Merr.] seed yield have been the focus of much research over the past four decades. However, most experiments were region-specific and focused on the effect of a single N-related management choice, thus resulting in a limited inference space. Here, we composited data from individual experiments conducted across the US that examined the effect of N fertilization on soybean yield. The combined database included 207 environments (experiment × year combinations) for a total of 5991 N-treated soybean yields. We used hierarchical modeling and conditional inference tree analysis on the combined dataset to establish the relationship and contribution of several N management choices on soybean yield. The N treatment variables were: N-application (single or split), N-method (soil incorporated, foliar, *etc.*), N-timing (pre-plant, at a reproductive stage, *etc.*), and N-rate (from a 0 N control to as much as 560 kg ha^{-1}). Of the total yield variability, 68% was associated with the effect of environment, whereas only a small fraction of that variability (< 1%) was attributable to each N variable. Averaged over all experiments, a single N application and the split N application were 60 and 110 kg ha^{-1} greater yielding than the zero N control treatment, respectively. A split N application with more than one method (*e.g.,* soil incorporated and foliar) resulted in 120 kg ha^{-1} greater yield than zero N plots. Split N application between planting and reproductive stages (Rn) resulted in greater yield than zero N and single application during a Rn; however, the effect was not significantly different than N application at other growth stages. Increasing the N rate increased the environment average soybean yield; however, 93% of the environment-specific N-rate responses were not significant which suggested a minimal effect of N across the examined region. A large yield variability was observed among environments

Abbreviations: BNF, biological nitrogen fixation; C, check (no nitrogen was applied); MM, major management practices; N, nitrogen; N-rate, nitrogen rate; N-application, number of nitrogen applications; N-method, method of nitrogen application; N-timing, timing of nitrogen application (growth stage/s); P, all nitrogen was applied at planting only; PR, split nitrogen application at planting and reproductive growth stages; pP, all nitrogen was applied at pre-planting only; Rn, reproductive growth stage; R, all nitrogen was applied at a reproductive growth stage only; RR, split nitrogen application at two reproductive growth stages; V, all nitrogen was applied at a vegetative growth stage only; Vn, vegetative growth stage

* Corresponding author.
E-mail address: mourtzinis@wisc.edu (S. Mourtzinis).

http://dx.doi.org/10.1016/j.fcr.2017.09.035
Received 27 June 2017; Received in revised form 28 September 2017; Accepted 28 September 2017
Available online 06 November 2017
0378-4290/

within the same N rates, which was attributed to growing environment differences (*e.g.*, in-season weather conditions, soil type *etc.*) and non-N related management (*e.g.*, irrigation). Conditional inference tree analysis identified N-timing and N-rate to be conditional to irrigation, and to seeding rates > 420,000 seeds ha^{-1}, indicating that N management decisions should take into account major, non-N related management practices. Overall, the analysis revealed that N management decisions had a measurable, but small, effect on soybean yield. Given the growing pressure for increasing food production, it is imperative to further examine all soybean N decisions (application method, timing, and rate) in environment- and cropping system-specific randomized trials in important agricultural regions.

1. Introduction

Soybean [*Glycine max* (L.) Merr.] is the most important oilseed crop in the USA, grown mainly as a protein and oil source for animal and human consumption. USA soybean production has increased by 60% from 1996 to 2016. The increase in soybean production is due to a 30% increase in area planted to soybean, and to better genetics and improved crop management practices that have resulted in a 35% increase in mean soybean seed yield (2,600–3,500 kg ha^{-1} between 1996 and 2016; USDA-NASS, 2017). While these historic seed yield increases have been substantial, USA soybean producers continually search for opportunities to optimize crop management and increase soybean seed yield, including applying fertilizer N to soybean.

Soybean has a large nutrient requirement throughout the growing season, and has an especially high N requirement due to its seed protein content that averages about 40% based on seed dry weight (Bellaloui et al., 2015). Analysis of 637 data sets, (site × year × treatment combinations) from 1966 to 2006, indicates a linear increase in N uptake in soybean aboveground biomass of 0.079 kg with each kg increase in seed yield (Salvagiotti et al., 2008). In a recent study conducted at multiple locations in Wisconsin and Minnesota, N content of soybean increased by 0.054 kg with each kg increase in seed yield (Gaspar et al., 2017). Soybean N requirements peak in the R3 to R6 growth stages (Harper and Cooper, 1971; Harper, 1974). Gaspar et al. (2017) reported that maximum daily N uptake rates (3.6–4.3 kg ha^{-1} d^{-1}) occur during the R4 to R5 (Fehr and Caviness, 1977) growth stages, whereas Bender et al. (2015) measured a greater daily N uptake rate of 4.6 kg ha^{-1} at R4 growth stage.

The N requirement of soybean is generally fulfilled by biological nitrogen fixation (BNF) plus N uptake from soil (Salvagiotti et al., 2008). Salvagiotti et al. (2008) reported that 50-60% of soybean N demand is fulfilled by BNF, whereas Harper (1974) found that 25 to 60% of N in soybean plants comes from BNF and the remaining 40 to 75% is provided from soil. Comparatively, greater contribution from BNF of near 90% (to seed N content) and 97% (to total plant N uptake) was reported by Mastrodomenico and Purcell (2012) and George et al. (1988), respectively. Zapata et al. (1987) concluded that maximum BNF occurs between the R1 and R4 stages, and biologically-fixed N (55%) contributes more to N assimilation in pods and seeds by the R7 growth stage compared to soil N (43%).

Based on lack of response to supplemental N applications, Freeborn et al. (2001) concluded that N supply through BNF and soil organic matter mineralization is sufficient for high soybean yields. However, BNF activity can be limited by a number of environmental conditions such as low soil moisture, extremes of soil pH and temperature, and soil compaction, any of which can result in insufficient N supply to the soybean plants (Purcell and King, 1996). Cold and saturated soil early in the growing season can slow the mineralization of organic matter and thus limit soil N availability to soybeans (Stanford et al., 1973; Stanford and Epstein, 1974). Maximum N mineralization rates occur when soil is at field capacity (0.3–0.1 bar matric suction), whereas saturated soils reduce N accumulation due to gaseous N losses by the denitrification process (Stanford and Epstein, 1974). Additionally, N mineralization increases when the temperature rises from 10 to 25°C (Agehara and Warncke, 2005). Stanford et al. (1977) reported a two-fold change in mineralization rate with a 10°C shift in soil temperature.

The quantity of soil N mineralized is also directly related to the organic N amount available in the soil. Although N may be limited early in the growing season, studies report that N supply by BNF during pod-filling (R4–R6) may lag behind N demand in high-yielding soybean (Wesley et al., 1998). Thibodeau and Jaworski (1975) reported that maximum BNF occurs at the early pod fill stage and again when seed development occurs at maximum rates. The high nitrogen requirement for soybean seed growth demands continued remobilization of N from vegetative tissues (Sinclair and de Wit, 1975), which reduces photosynthetic capacity of leaves and accelerates leaf senescence, and can restrict duration of the seed-fill period which thus reduces seed yield potential. Any gap between soybean N demand and N supply by BNF thus needs to be supplied *via* other N sources in order to reduce the gap between the realized soybean seed yield and its potential. One strategy for closing this gap is the application of N fertilizer to soybean, particularly when the crop is subjected to adverse growing conditions or produced in high-yield environments.

Extensive research to date has documented the impacts of N fertilizer source, application rate, application method, and seasonal timing on USA soybean yield. Many of these studies show inconsistent response of soybean yield to N application within and across states. For example, N applications of 50 kg ha^{-1} at planting resulted in 8% increase in soybean seed yield in Alabama (Starling et al., 1998), and a 12% increase in soybean yield in Kansas when N (22–45 kg ha^{-1}) was applied at R3 stage (Wesley et al., 1998). In an earlier study, Brevedan et al. (1978) observed a 28–32% increase in soybean seed yield in Kentucky, which the authors attributed to increased nodes $plant^{-1}$, seeds $plant^{-1}$, and seed mass, plus decreased flower and pod abortion. In two different studies conducted in Mississippi on clay soil, soybean seed yield was increased by 8% with 90–179 kg N ha^{-1} irrespective of application at V4 or R1 (McCoy, 2016), and by 15% with 260–360 kg N ha^{-1} when applied during early vegetative growth (Vn) (Ray et al., 2006). In Nebraska, soybean yields increased by 5% when fertilized with 180 kg N ha^{-1} compared to unfertilized soybeans (Salvagiotti et al., 2009). In other studies in Nebraska, differences in test site soil pH, soil organic matter, yield level, irrigation, and residual soil nitrate content resulted in inconsistent soybean response to N application between years (Sorensen and Penas, 1978; Al-Ithawi et al., 1980). These results highlight the challenge in predicting the conditions favorable for, and the magnitude of, soybean yield response to N applications.

Influence of initial soil nitrate-N content on soybean response to N fertilizations also has been reported in previous studies (Stone et al., 1985; Lamb et al., 1990; Wood et al., 1993; Scharf and Wiebold, 2003). In Missouri studies, a small yield response to N application (33 kg ha^{-1}) was observed only on soils with soil pH < 6 and nitrate-N content $<$ 56 kg ha^{-1} in the top 61 cm depth (Scharf and Wiebold, 2003). Lamb et al. (1990) and Stone et al. (1985) observed that soybean responded to N fertilizer only when soil nitrate-N content was < 90 kg ha^{-1} (0–61 cm soil depth) and < 190 kg ha^{-1} (0–180 cm soil depth), respectively. Similarly, Stone et al. (1985) found that for each 1 kg ha^{-1} increase in soil nitrate-N content, the soybean yield benefit from N fertilization decreased by 4 kg ha^{-1}. High levels of soil N (application rate of 90–200 kg ha^{-1}, or a 4–7.5 mM soil nitrate concentration)