REVISING THE IMPACTS OF LATE SEASON NITROGEN FERTILIZATION ON WHEAT CROPS

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ABSTRACT

Late-season applied N is a challenging practice that when used correctly can contribute to the sustainability of grain production systems by maintaining grain yield and improving grain quality. A systematic assessment of the effects of late-applied N across multiple environments and agronomic practices is currently lacking. Therefore, our goals were to determine the impact of late-season N application on wheat grain yield and protein concentration (GPC) through the utilization of meta-analytic models; and to determine which fertilizer management scenarios were moderating these effects. A systematic literature search was performed for articles reporting grain yield and grain protein, biomass and N uptake at plant maturity. Across studies, grain yield was unaffected by late season nitrogen; however, the effect on grain protein concentration was significantly positive with a pooled estimate of 3.7%. Significant heterogeneity (I^2 = 78%) for grain protein concentration suggested the need for further exploration of potential moderators. Increasing the proportion of late season N rate over the total N available for the crop in the season was positively related to protein gains, decreasing the I^2 to 54%.

INTRODUCTION

Synchronizing N supply and demand can a tactical strategy for further improving N use efficiency and reducing losses in wheat production systems (Foulkes et al., 2009; Hawkesford, 2014). Through management, this can be achieved by delaying N applications until a moment in which (i) crop yield (being one of the main drivers of N requirements) could be more accurately predicted (Raun and Johnson, 1999); (ii) allows to detect N deficient zones through ground-based reflectance sensors and thus adjust spatially variable rates as a function of crop needs (Raun et al., 2005); (iii) the root system is fully developed and thus positively correlates with higher N uptake efficiency (Foulkes et al., 2009). Therefore, it is crucial to assess late-season N relevance on grain quantity and quality, underpinning its constraints and synergies with management, physiological, and environmental factors.

Across the literature, there is a strong agreement on lack of yield response when N is applied surroundings anthesis(Altman et al., 1983; Woolfolk et al., 2002; Blandino et al., 2015, 2020; Lollato et al., 2021). Nonetheless, there are particular situations in which there is still place for improving yields. For instance, Rossmann et al. (2019) reported yield increases when N was applied at anthesis only for two particular genotype × N regime combinations.

Even though late-season N fertilization has extensively demonstrated clear benefits on wheat protein and quality (Blandino et al., 2015; Cruppe et al., 2017; Lollato et al., 2021), no attempts have been made to quantify its impact on a wide range of environmental conditions.

Furthermore, literature highlights variable response to late season N depending upon management practices adopted (Finney et al., 1957; Woolfolk et al., 2002; Bly and Woodard, 2003; Cruppe et al., 2017), plant N status at anthesis (Varinderpal-Singh et al., 2012) and at a greater extent the environmental conditions explored during the post anthesis period (Bogard et al., 2010).

Therefore, our objective was to perform a comprehensive literature synthesis of N applications post Zadoks 3.7 to: (i) quantify the its overall impact on wheat grain yield and protein concentration and; (ii) to compare whether these effects are affected by different late-season N fertilizer management practices (rates, timing, placement, source).

MATERIALS AND METHODS

A literature search was performed to assess the effect of late-season N application in wheat. We screened articles published in *Agronomy Journal, Crop Science, European Journal of Agronomy, and Field Crops Research.* Data from thesis, dissertation, or unpublished trials were also considered to avoid publication bias (McLeod and Weisz, 2004). The search terms included the word *'wheat'* and any of the following words: *'nitrogen', 'yield', 'protein'* in the article title. The search resulted in 1,672 publications (294-637 per journal), all of which were scanned seeking for specific criteria as requirements for manuscript inclusion in the database. Criteria was fulfilled when: (i) Studies were reporting N applications before and after GS 37 (flag leaf visible); (ii) Either grain yield or grain protein concentration values were reported directly or indirectly (iii) Data were collected only when individual environments were reported (not aggregated across environments); (iv) control (Zero N) and Basal N treatments were reported; (v) when timing of application was not clearly defined and not explicitly determined in any of the well-known Zadoks (1974) or Feekes (Large, 1954) wheat development scales; (vi) data included were considered only from field studies.

Different late-season N management scenarios were defined: (i) timing of application, as indicated in articles expressed in Zadoks growth stage units (Zadoks et al., 1974); (ii) source; (iii) placement; and (iv) rate. Together with the late N rate (LNR), we also collected the early N application rate (ENR) and total $N - NO_3$ at sowing. Subsequently, the total nitrogen available for the crop was calculated as:

$$TN(kgN\,ha^{-1}) = N - NO_3(kgN\,ha^{-1}) + ENR(kgN\,ha^{-1}) + LNR(kgN\,ha^{-1}) \quad \textit{Eq. 1}$$

Derived from Eq. 1 we calculated the Ratio, as the proportion of late season N rate over the total N available for the crop during the season. Nitrogen sources were categorized into five categories: (i) foliar sources, (ii) dry ammonium nitrate, (iii) diluted ammonium nitrate, (iv) dry urea, and (v) diluted urea. Nitrogen placement groups were defined as "soil" and "foliar".

Late-season N effects on grain yield and GPC were calculated as the natural logarithm of the response ratio between treatments that received late-season N and the corresponding control treatment that received otherwise the exact same previous agronomic management. For the easiness of interpretation, we calculated the aproportional effect in the fertilized group relative to the control group as *Eq. 3.* Effects were weighed according to the inverse of the pooled sampling variance between the two groups being compared.

$$Effect\,(\%) = \left\{\frac{\bar{X}_{fertilized}}{\bar{X}_{control}} - 1\right\} * 100 \quad Eq. 3$$

RESULTS AND DISCUSSION

Late season N did not affect grain yield across a wide range of environments and management practices (Table 1). Analysis of residual heterogeneity showed that these effects were very consistent reflected by a low I^2 of 35%. Our results were in line with previous research reporting lack of yield response to different management practices related to late season N even in interaction with genotype (Altman et al., 1983; Bly and Woodard, 2003), environment (Altman et al., 1983; Bly and Woodard, 2003; Dick et al., 2016; Cruppe et al., 2017), genotype × environment (Altman et al., 1983; Bly and Woodard, 2003).

Table 1. Overall effect (mean estimate and its respective 95% confidence interval – lower (LB) and upper bounds (UB) are presented) for grain yield and GPC. Asterisks represent significance of the effects at α = 0.01 (***)

Pooled estimate	**Grain Yield Response (%)**	**Grain Protein Concentration Response (%)**
Mean	0.7	3.7 ***
LB 95% CI	-2.19	0.7
UP 95% CI	3.68	6.9
I^2(%)	35	78

Delaying N applications resulted in positive significant impact on protein (Table 1). However, these results were highly heterogeneous (I^2 = 78%), meaning there could be potential factors controlling the magnitude of the response. Ratio positively correlated to protein and reduced the inconsistency up to 54% (I^2) (Table 2). Timing of N application was unrelated to protein response (Table 2). From our data we found that when N was soil placed protein response was greater as compared with foliar N treatments (Table 2). Dry ammonium and foliar fertilizers were sources that resulted in significant protein response (p> 0.05; Table 2). Situations in which dry ammonium nitrate and foliars were applied, protein was 8.6% and 4.6% respectively. However, protein was moderately impacted by dry urea (5.8%), diluted ammonium nitrate (3.28%), diluted urea (2.4%). Even though ammonium nitrate had the greatest protein response, results are still heterogeneous when accounting for fertilizer sources single effects (I^2 = 63%).

Table 2. Effect of management practices over GPC response to late season N fertilization. (mean estimate and its respective 95% confidence interval – lower (LB) and upper bounds (UB) are presented). Asterisks represent significance of the effects at α = 0.05 (**) and α = 0.01(***).

			Grain Protein Concentration Response (%)			
			Mean	**LB 95% CI**	**UP 95% CI**	**I^2 (%)**
Management	Placement	Soil	7.09**	3.15	11.17	60
		Foliar	3.94**	0.99	6.97	
	Source	Foliar	4.58**	1.36	7.91	63
		Dry Urea	5.87	-0.35	12.49	
		Dry Ammonium	3.28**	2.49	15.08	
		Diluted Urea	2.38	-3.08	8.17	
		Diluted Ammonium	8.6	-3.24	10.24	
			Slope		**I^2(%)**	
	Ratio		26.1 ***		54	
	Timing		ns		62	

CONCLUSION

Our review remarks late-season N have negligible impacts on grain yield and these effects were highly consistent across the wide range of environments and agronomic practices explored in this analysis. In contrast, grain protein concentration responded positively to late season N and these effects resulted highly heterogeneous. Notwithstanding, late-season N management can provide enlightenment for reducing these inconsistencies. This review provides evidence on how the proportion of N applied late in the season over the total available N for the crop controls grain protein response and thus reduce heterogeneity. Still, the great dispersion of the data, shows how grain protein response to delayed N applications is strongly governed by complex G × E × M interactions, all of which is being addressed in current research.

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