Maize nitrogen management in soils with influencing water tables within optimum depth

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ABSTRACT

The central temperate Argentinean region is currently affected by rising water tables, allowing higher and more stable maize yields (*Zea mays* L) when they fluctuate within optimum depth. However, limited information was available for optimizing N management in these environments. Yield response to N rates was explored in soils with influencing groundwater (always less than 3.5 m depth), and different environment and management variables were examined to help explain differential yield responses across sites. A total of 15 rainfed experiments (site × year combinations) were conducted with five N rates (0 to 240 kg N ha^{-1}) tested at two different timings (sowing and V7) in a factorial design. A consistent yield response to N rate was evident, increasing yields from 2300 to 6900 kg ha^{-1} across sites. Yields at maximum N levels ranged from 13700 to 16900 kg ha^{-1}. Fertilization timing had a minor and inconsistent effect on yield across sites. At a maize grain:fertilizer N price ratio of 10, the economically optimal N rate ranged from 117 and 206 kg N ha^{-1}. Soil N-NO$_3$ at sowing, previous crop, and apparent-INS (apparent-indigenous N supply) helped explain differential yield responses across sites, and response models for obtaining economic optimum rates considering the influence of these variables are provided. These results highlight the relevance of N rate, rather than timing, as a critical crop management decision in environments with high water availability and yield.

Abbreviations: AIC, Akaike's information criterion; apparent-INS, apparent-indigenous N supply; SOM, soil organic matter; N$_{an}$, anaerobic N; REML, restricted maximum likelihood.

Food production is challenged by a growing population that demands increased crop productivity and reduced agricultural environmental impact (Andrade et al., 2017). Yield gaps must be closed while incrementing water and nutrients efficiency in order to diminish the environmental footprint of agriculture

(Foley et al., 2011). Resource-use efficiency increases with a better understanding of crop requirements and nutrient dynamics, where on-farm development and adoption of better agronomic practices is essential (Tilman et al., 2002). For this, environment x nutrient management interactions need to be considered in any fertilization decision (Morris et al., 2018). In 2019, Argentina was the fourth global maize producer and second largest exporter (USDA-FAS, 2020). Like in most rainfed maize production systems, water and N availability are two major constraints in this country (Aramburu Merlos et al., 2015).

While water availability is a main limitation for maize production worldwide, in many areas of the Argentinean central temperate region crop production is influenced by water tables (from soil surface to 4 m depth; Nosetto et al., 2009). This region is considered an hyper plain, characterized by a very low regional topographic gradient (<0.1%), where vertical water movements prevail on horizontal (Jobbágy et al., 2008). Annual crops replaced grasslands during the last 30 to 40 years, reducing annual water evapotranspiration and resulting in the recharge of water basins and rise of water tables (Nosetto et al., 2012). This rise impacted crop water availability, adding in some cases more than 300 mm of water (i.e., half of maize water requirements; Portela et al., 2009) and helping achieve high and more stable yields when water table fluctuates around optimum levels (1.4 to 2.45 m depth; Nosetto et al., 2009; Rizzo et al., 2018). However, local studies also showed that shallow groundwater levels can have negative effects on maize yields under high rainfall levels (Vitantonio-Mazzini et al., 2020), especially when soil water tables are less than 1.4 m depth from soil surface, causing roots and plant death, salinization, and N loses (Nosetto et al., 2009; 2012).

Maize yield response to N rate depends on attainable yield and on the intrinsic capacity of the soil to deliver N (Salvagiotti et al., 2011). This yield response is commonly curvilinear, following the law of decreasing increments, and can be modeled with quadratic, exponential, logistic, linear-plateau, or quadratic–plateau response functions, among others (Cerrato and Blackmer, 1990; Pagani et al., 2008; Salvagiotti et al., 2011; Correndo, 2018). In Argentina, N fertilizer recommendations are commonly based on soil N-NO_3 content before sowing from surface to 60 cm depth as an indicator of soil N availability (Magdoff et al., 1984; Pagani et al., 2008; Salvagiotti et al., 2011). This test only accounts for a fraction of soil N supply, and does not consider the contribution of soil organic matter (SOM) mineralization, during the cropping season. Other methodologies include the measurement of soil N-NO_3 availability at V3-V4 (Magdoff et al., 1984; Salvagiotti et al., 2001; Pagani et al., 2008) or the use of anaerobic N (N_{an}; Sainz Rosas et al., 2008; Orcellet et al., 2017). Recent studies provided more complex models for Argentina, including genotype, environment and crop management variables to help explain yield response to N (Gambin et al., 2016; Coyos et al., 2018; Correndo, 2018; Puntel et al., 2019). However, there is a knowledge gap about yield responses to N rate in environments influenced by water tables that fluctuate around optimum levels, where higher than average yields are commonly expected.

Nitrogen fertilization timing can affect N use efficiency in environments with high water availability. During early vegetative stages maize N requirements are low, increasing after V6 and maximized between V12 and flowering (Russelle et al., 1983; Ciampitti and Vyn, 2012). Optimum synchronization between N availability and crop demand reduces the N losses and increase N use efficiency

(Chen et al., 2006). We speculate that N fertilization timing can be particularly relevant for environments with higher risk of N loss, as may happen in soils with influencing water tables and potential water-logging, where N application at sowing might have low efficiencies and may lead to N fertilizer pollution (Sainz Rosas et al., 2001). Nonetheless, it is also known that in some environments delays in N fertilization can generate N deficiencies early in the cropping season, affecting attainable yield (Binder et al., 2000; Walsh et al., 2012). Previous local research on N timing was conducted in soils with no presence of an influencing water table (Sainz Rosas et al., 2001; 2004).

The objectives of our study were to: (i) quantify maize yield response to N rate in two timings (sowing and V7) in soils with influencing water tables, and (ii) identify environment and management variables that can explain yield response differences to N rate. To address these objectives, we conducted fifteen N response experiments in environments with an influencing water table. We hypothesized a delay in N application to early vegetative stages will increase yield responses as compared with N fertilization at sowing.

MATERIALS AND METHODS

Crop management and N fertilization treatments

Fifteen on-farm experiments were conducted within a limited area of 3000 km^2 in southeast Córdoba province (Figure 1) during 2016/2017 and 2017/2018 cropping seasons (hereinafter Years 1 and 2, respectively). This region has frequent influence of water table (less than 4 m depth; Nosetto et al., 2012; Vitantonio-Mazzini et al., 2020). Seven experiments were conducted in Year 1 and eight in Year 2. The specific location of each experiment differed within each year, consequently each combination of experiment x year was treated as individual experiments (hereinafter site). Site characteristics are listed in Table 1, named by farmer and harvest year. All fields belong to farmers grouped within AAPRESID, the Argentinean Association of No-Tillage Farmers. Soils were predominantly deep silty loams (typic Hapludoll and hudic Haplustoll) and deep clay loam soils (typic Argiudoll; Soil Survey Staff, 2014), commonly used for maize production in the region (soils productivity IIc).

Fields were managed under no-tillage and rainfed conditions. Crop management followed common agricultural practices in terms of hybrid, plant density, row spacing, and P, S, and Zn fertilization, and were decided independently by each individual farmer. Crops were sown using farmers' available technology (planter, sprayer), and weeds and insects were controlled using standard practices. Inter-row spacing was always 0.52 m. Sowing date ranged from September 16 to October 23, and stand density from 7.2 to 9.0 plants m^{-2}. Previous crop was double crop wheat/soybean (*Triticum aestivum* and *Glycine max*) in most sites, with the exception of five sites (Pz_1, Th_1, Mz_1, Pg_2, and Ro_2) where the previous crop was single soybean.

Treatments consisted in five N rates (0, 60, 120, 180, and 240 kg N ha^{-1}) and two fertilization timings (sowing and V7 leaf stage; Abendroth et al., 2011), totaling 10 treatment combinations. Treatments were arranged in a completely randomized factorial design with three replicates, except one site (Mzi_2) that had two replicates. Individual plots were 53 m^2. Fertilizer was manually spread, and N source was urea (46-0-0) treated with n-butyl thiophosphoric triamide (NBPT) to reduce volatilization losses.

Soil and crop determinations

A few days before sowing, soil samples from surface to 60 cm depth at 20 cm intervals were taken in each site. At V4, two additional samplings were made in plots corresponding to zero N rate treatment, one from surface to 60 cm depth with 20 cm intervals similar to the one done at sowing, and a second from surface to 30 cm depth. All samples were immediately air-dried until constant weight and sieved with a 2 mm mesh. For the sowing sample from surface to 20 cm depth, SOM (Walkley and Black, 1934), N_{an} (7 days incubation; Bremner and Keeney, 1965), extractable phosphorus (Bray-I P; Bray and Kurtz, 1945), apparent electric conductivity, and pH were determined. Soil $N\text{-}NO_3$ content (kg ha^{-1}; Keeney and Nelson, 1982) was quantified to all surface to 60 cm samples taken at sowing and at V4, and to the single sample from surface to 30 cm depth taken at V4. Soil $N\text{-}NO_3$ content was calculated assuming a 1.25 Mg m^{-3} soil bulk density.

At sowing, soil available water content was determined gravimetrically at each experiment up to 2 m depth (Black, 1965) and expressed as a percentage of the maximum water holding capacity between soil wilting point and field-capacity. Depth of soil water table was measured at sowing and at physiological maturity with a monitoring well installed in each experiment up to 4.0 m depth. Rainfall during the cropping season was recorded in each experiment.

At physiological maturity above ground plant biomass was determined in plots corresponding to zero N rate treatment by sampling one square meter per replicate. Plants were dried in an air-forced oven at 65°C until constant weight. Grain and vegetative structures were weighted and milled separately. N concentration in both structures was determined by micro-Kjeldahl (Mckenzie and Wallace, 1953). Apparent-indigenous N supply (apparent-INS) is the total N in aboveground biomass in the zero N rate treatments at physiological maturity, as estimated by Cassman et al. (1996).

At harvest maturity grain yield was determined in a 7.4 m^2 area in the center of each replicate, and grain yield is reported with 140 g kg^{-1} moisture content.

Statistical Analysis

Data was analyzed using linear mixed-effects models (lme4 package, lmer function; Bates et al., 2015) in R version 3.3.0 (R Core Team, 2016). Two independent analyses were done. First, analysis of variance was performed in order to explore yield variations associated with each effect (site, N rate, timing, and all possible interactions), considering N rate as a discrete variable. Mean comparisons between fertilization timing across sites and N rates were done using LSD at 0.05 probability level with the *predictmeans* function in R (Luo et al., 2020).

In the second analysis linear mixed-effects models were performed, incorporating management or environmental explanatory variables at the site level to explain yield response to N rate for the entire data set. For this second analysis, data exploration and model selection were done similarly to Coyos et al. (2018) or Gambin et al. (2016), following the steps described in Zuur et al. (2009). These steps involve (i) data exploration, (ii) model fitting, and (iii) model validation.

Data exploration suggested a curvilinear relationship between yield and N rate. A quadratic model was fitted with N rate as fixed quantitative predictor to explore site to site variations in yield response to N rate (model A). The random terms considered the variation on the intercept (i.e., grain yield at zero N rate treatments) for the different sites, the N rate x site interaction in order to explore site to site variation in their yield response to N rate, and the fertilization timing. Yield at each site and N rate level was modeled as:

$$Y_{ij} = \beta_{0j} + \beta_{1j} N_i + \beta_{2j} N_i^2 + \sigma_{ij} \qquad \text{(equation 1)}$$

where Y_{ij} is the yield at i level of N rate at site j, β_{0j} is yield at the zero N rate treatment in site j (kg ha^{-1}), β_{1j} represents the effect of N rate at N_i level in site j (kg ha^{-1} grain per kg ha^{-1} N), β_{2j} represents the quadratic component of N rate at N_i level in site j, and σ_{ij} encompasses the random term corresponding to fertilization timing effect plus error. Other random structures explored (timing nested within site) indicated some evidence of model degenerates associated with increased complexity of random structure that is not supported by the data. This may lead to a significant loss of power (Matuschek et al., 2017). For this reason, we decided to keep the simplest random structure supported by the data, resulting in parsimonious models. Random terms were assumed to be normally distributed with a mean of zero and constant variance. Model was fitted using REML (restricted maximum likelihood) estimations.

The inclusion of an explanatory variable into the model was determined by exploring the correlation between each variable and parameters describing yield variation across sites (β_{0j}) and the coefficients of the yield response to N rate obtained in equation 1 (β_{1j} and β_{2j}). Explored variables (Table 1) were soil type (analyzed as qualitative with three levels: Typic Hapludoll, Hudic Haplustoll, and Typic Argiudoll), sowing date (days after 1 September), stand density, previous crop (analyzed as qualitative with two levels, soybean or wheat/soybean), soil water content (as percentage of maximum water holding capacity at sowing, 0-2 m depth), rainfall during the cropping season (mm), depth of water table at sowing (analyzed as qualitative with two levels, ≤1 m or > 1 m depth), SOM (%, 0-20 cm depth), soil N-NO_3 at sowing (kg ha^{-1}, 0-60 cm depth), soil N_{an} (ppm, 0-20 cm depth), soil phosphorus (ppm, 0-20 cm depth), soil conductivity (mmhos cm^{-1}, 0-20 cm depth), pH (0-20 cm depth), soil N-NO_3 at V4 up to 60 cm depth (kg ha^{-1}, 0-60 cm depth), soil N-NO_3 at V4 up to 30 cm depth (kg ha^{-1}, 0-30 cm depth), and apparent-INS (kg ha^{-1}). This analysis suggested that explanatory variables in the fixed component that were most likely to contribute to the optimal model were three: soil N-NO_3 at sowing from surface to 60 cm depth, previous crop, and apparent-INS. These variables correlates with parameters β_{0j} and β_{1j}. Although the correlation between β_{0j} and apparent-INS is spurious because both are estimated from yield at zero N rate treatments, the variable apparent-INS was used with explanatory purposes as an indirect indicator of soil N supply. No rational correlations were found between β_{2j} and variables.

In model fitting, multicollinearity was detected between explanatory variables. Soil N-NO_3 at sowing and apparent-INS were higher when previous crop was soybean than double crop wheat/soybean ($p<0.05$). Also, a correlation between soil N-NO_3 at sowing and apparent-INS was evident ($r = 0.62$; $p<0.05$). Consequently, three different final models were proposed (one for each explanatory variable). These models considered the effect of N rate at the individual level, and the interactions N rate x apparent-INS (model B), N rate x soil N-NO_3 at sowing (model C), and N rate x previous crop (model D). In each final model, yield was as:

$$Y_{ij} = \beta_{0j} + \beta_{1j} N_i + \beta_{2j} N_i^2 + \sigma_{ij} \qquad \text{(equation 2)}$$

where

$$\beta_{0j} \sim N\left(\mu_{\beta_{0j}}; \sigma^2_{\beta_0}\right) \text{ and } \mu_{\beta_{0j}} = \alpha_0 + \alpha_n P_j \qquad \text{(equation 3)}$$

$$\beta_{1j} \sim N\left(\mu_{\beta_{1j}}; \sigma^2_{\beta_1}\right) \text{ and } \mu_{\beta_{1j}} = \gamma_0 + \gamma_n P_j \qquad \text{(equation 4)}$$

$$\beta_{2j} \sim N\left(\mu_{\beta_{2j}}; \sigma^2_{\beta_2}\right) \text{ and } \mu_{\beta_{2j}} = \delta_0 + \delta_n P_j \qquad \text{(equation 5)}$$

Note that equation 2 is the same as equation 1, but now β_{0j}, β_{1j} and β_{2j} are dependent on explanatory variables at the grouping level (site) with consequences to the coefficient estimates. Explanatory variable P will depend on the particular model, being apparent-INS in model B, soil N-NO_3 at sowing in model C, and previous crop in model D. For example, for model B, β_{0j} depends on a constant fixed term α_0 and the fixed effect of apparent-INS (α_1; equation 3). β_{1j} depends on a constant fixed term γ_0, and the fixed effect of apparent-INS (γ_1). Similarly, β_{2j} depends on a constant fixed term δ_0, and the fixed effect of apparent-INS (δ_1).

In model validation, we checked the Gaussian distribution and homoscedasticity assumptions (Zuur et al., 2009) for the standardized model residuals with graphical analysis. There was no covariance among random effects. Final models were presented using REML, and were compared using the Akaike's information criterion (AIC). AIC is an appropriate tool for model comparison (Aho et al., 2014; Burnham and Anderson, 2002; Burnham et al., 2011). R^2 of adjusted models were obtained following the methodology described in Nakagawa and Schielzeth (2013) for generalized linear mixed models, similarly to Gambin et al. (2016). Marginal R^2 (R^2_m) represents the variance explained by fixed effects while conditional R^2 ($R^2{}_c$) represents the variance explained by the entire model (fixed and random effects; Nakagawa and Schielzeth, 2013).

RESULTS

Explored environment variations

Environment variables showed ample variation across sites (Table 1). Soil available water content at sowing across sites was always above 90% of maximum water holding capacity. All sites presented a water table close to soil surface, ranging from 0.7 to 2.0 m at sowing, and between 2.0 and 3.5 m at physiological maturity. Rainfall from sowing to physiological maturity varied across sites, ranging from 325 to 498 mm. Soil organic matter varied from 2.3 to 2.8%, and N_{an} from 39 to 64 ppm. Soil N-NO_3 at sowing (from surface to 60 cm depth) ranged from 50 to 74 kg N ha^{-1}, and at V4 the zero N rate treatment showed 40 to 91 kg N ha^{-1} from surface to 60 cm depth and 13 to 43 kg N ha^{-1} from surface to 30 cm depth. Soil P ranged from 8 to 35 ppm. Apparent-INS varied from 82 to 158 kg N ha^{-1} across sites (Table 1). In the zero N rate treatments, grain N concentration varied from 0.81 and 0.95%, and N harvest index ranged from 0.63 to 0.71 (data not shown). Apparent-INS was not correlated with N_{an} or SOM. Soil N-NO_3 at sowing ($r = 0.62$; $p<0.05$) and previous crop ($p<0.05$) were the only variables significantly associated with apparent-INS.

Response to N rate at different timings across sites

Yield in the zero N rate ranged from 7600 to 12800 kg ha^{-1}, while maximum yields obtained in the highest N fertilization rate (i.e., 240 kg N ha^{-1}) ranged from 13700 to 16900 kg ha^{-1} (Figure 2A). Significant yield differences were observed between sites ($p<0.001$) and N rates ($p<0.001$; Table 2). However, significant site x N rate, site x fertilization timing, and N rate x fertilization timing interactions were evident. These interactions showed that yield response to N rate was different among sites, and that the fertilization timing effect differed across sites and N rates. N rate explained 57.6% of total grain yield variation, while the site and site x N rate interactions explained 19.7 and 7.4% yield variations, respectively. Fertilization timing had a minor effect through its significant interactions site x timing and N rate x timing, explaining 3.7 and 0.9% of total yield variability, respectively (Table 2).

A higher site to site yield variation was observed in the zero N rate treatments than in the maximum N rates (CV 17 vs. 6%). On average, grain yield increased 4544 kg ha^{-1} from 0 to 240 kg N ha^{-1} (ca. 42%), ranging from 2300 to 6900 kg ha^{-1} across sites. The yield increase observed in each site was significantly correlated with the site yield in the zero N rate treatments ($r = -0.81$; $p<0.01$) but not with maximum observed site yield. Maximum site yields were not correlated with the observed yield in the zero N rate treatments.

Fertilization timing had a significant effect on yield only in five sites. In two sites yield was on average 1457 kg ha^{-1} higher when fertilized at sowing when compared to V7, and in three sites yield was on average 995 kg ha^{-1} lower at sowing than in V7 (Figure 2B). Interestingly, no differences between fertilization timings were observed when the yield of the zero N rate treatments was above 10000 kg ha^{-1} (Figure 2).

Differences between timings were significant at 60 and 240 kg N ha^{-1} rates ($p<0.05$). At 60 kg N ha^{-1}, yield was 494 kg ha^{-1} higher when applying at V7 than at sowing. In contrast, at 240 kg N ha^{-1}, yield was 474 kg ha^{-1} higher when applying at sowing compared to V7 (Suppl. Figure S1).

Site-specific variables affecting yield response to N rate

The second goal was to explore environment and management variables that can help explain yield response differences to N rate across sites. In the previous section, important site to site variations in yield and in yield response to N rate were confirmed, while fertilization timing had comparatively less influence on yield (Table 2). For this, model A (equation 1) was fitted, which considered intercept variation due to each site, a N rate x site interaction term added to explore site to site variations in yield response to N rate, and a fertilization timing effect term. Model A is described in Figure 3, showing variations in intercept and slopes between sites. Parameter β_{0j} ranged from 7783 to 13056 kg ha^{-1} across sites, β_{1j} ranged from 23.7 to 58.8 kg ha^{-1} per kg N rate ha^{-1}, and β_{2j} from -0.13 to -0.07 kg ha^{-1} per kg N rate ha^{-1} (Suppl. Table S1). The R^2 of the model was 0.88 (R$^2{}_c$).

Data exploration suggested that the explanatory variables that could be used to explain yield response differences to N rate across sites were apparent-INS, soil N-NO$_3$ at sowing (Suppl. Table S2), and previous crop. Intercept (β_{0j}) was higher in sites with soybean as previous crop than in sites with double crop wheat/soybean (12200 vs. 10105 kg ha^{-1}, respectively; $p<0.05$; Figure 4), and the yield response to N rate (β_{1j}) was lower in sites with soybean than wheat/soybean as previous crop (31.4 vs. 46.6 kg ha^{-1} per kg N rate ha^{-1}, respectively; $p<0.01$). Soil N-NO$_3$ at sowing and apparent-INS were both positively associated with intercept value (β_{0j}), and negatively with yield response to N rate (β_{1j}; Figure 4).

Three final models were proposed, one for each explanatory variable. Model B, C, and D added the effects of apparent-INS, soil N-NO$_3$ at sowing, and previous crop, respectively, as well as the interaction between each variable with N rate

(Table 3). R^2_m ranged from 0.37 to 0.83, and R^2_c ranged from 0.83 to 0.90 across models (Table 3).

Regression coefficient estimates for the three final models allowed quantifying the specific influence of each explanatory variable on grain yield and yield response to N rate. Apparent-INS had a positive effect on yield of 72.1 kg ha^{-1} per kg apparent-INS ha^{-1}. The response to N rate decreased at a rate of 0.3 kg ha^{-1} per kg apparent-INS ha^{-1}, as indicated by the linear coefficient (model B; Table 3). Similarly, soil N-NO$_3$ at sowing had a positive effect on yield of 152.3 kg ha^{-1} per kg soil N-NO$_3$ ha^{-1}, and the response to N rate decreased at a rate of 1.0 kg ha^{-1} per kg soil N-NO$_3$ ha^{-1} (model C; Table 3). Finally, double crop wheat/soybean as a previous crop decreased yield by 2024 kg ha^{-1}, but increased yield response to N rate in 9.7 kg ha^{-1} per kg N rate ha^{-1} (model D; Table 3). Final models correctly described yield responses to N rate across sites (Figure 5).

We used information provided in Table 3 for calculating the parameters β_{0j}, β_{1j} and β_{2j} of a typical quadratic yield response to N rate function, but considering site variables that affect yield response to N rate. Figure 6 provides a graphical representation of these models. Lines represent the expected yield for different N rates after considering different levels of apparent-INS, soil N-NO$_3$ at sowing, or previous crop. Based on model B, the impact of apparent-INS is important in obtaining a higher yield at zero N rate and in reducing the yield response to N rate. Similarly, model C indicated that the impact of soil N-NO$_3$ results in a higher yield at zero N rate and reduces the yield response to N rate. Finally, model D indicated that soybean as previous crop results in higher yields with limited N applications and reduces the yield response to N rate when compared to wheat/soybean.

Based on models presented in Figure 6, economic optimal N rates were estimated by equalizing the first derivative of the quadratic function with relative prices of fertilizer and grain. For this, an expected grain:N price ratio of 10:1 (Salvagiotti et al., 2011; Enrico et al., 2020) was considered. Model B indicated that the economic optimal N rate was approximately 206 kg N ha^{-1} at 80 kg ha^{-1} of apparent-INS, or 117 kg N ha^{-1} when apparent-INS was 160 kg ha^{-1}. For model C, the optimal rate was 191 kg N ha^{-1} for 50 kg ha^{-1} of N-NO_3 at sowing, or 121 kg ha^{-1} when N-NO_3 at sowing was 75 kg ha^{-1}. Contemplating model D, if the previous crop is soybean the economic optimal N rate approximates 128 kg N ha^{-1}, while 184 kg ha^{-1} with wheat/soybean as previous crops.

DISCUSSION

A common concern among farmers and advisors in our focus region was the limited information regarding N fertilization management in highly productive environments with influencing water tables fluctuating around optimum depths. As far as we know, this concern was never addressed in other regions with similar environmental context. The environments analyzed in the present study presented water tables at sowing that ranged from 0.7 to 2.0 m depth, and showed large initial yield responses to N rate (average 41.6 kg grain kg N^{-1}). The observed yield difference between the two most extreme fertilizer rates 0 and 240 kg N ha^{-1} was 4544 kg ha^{-1}, and economic optimal N rates (considering an expected grain:N price ratio of 10:1) obtained from the final proposed models ranged from 117 and 206 kg N ha^{-1}. These rates allowed average yields across sites of ca. 15000 kg ha^{-1}.

The calculated economic optimal N rates were higher than those commonly used by farmers in the region (96 kg N ha^{-1}, Bolsa de Cereales, 2020). Yield responses to N rate were also higher than the ones obtained in previous studies carried in the temperate central region of Argentina for early sown maize crops (Gudelj et al., 2000; Sainz Rozas et al., 2008; Salvagiotti et al., 2011; Zorzín and Ioele 2012; Vitantonio-Mazzini et al., 2020). US corn belt states commonly use the so-called maximum return to N (MRTN) approach for N-rate decisions (Sawyer et al., 2006), mainly because optimum N relationship with yield is erratic. In the present study, yield response to N rate depended more on the yield at the zero N rate treatment than on maximum attainable yields, differing from results obtained by Salvagiotti et al. (2011) and Pagani et al. (2008). We hypothesize this is because in environments with water tables fluctuating under optimum depths, maize N and water requirements were mostly covered in the 240 kg N ha^{-1} treatment, resulting in similar site to site maximum attainable yields (CV 6%).

Fertilization timing had a minor effect on yield that varied across sites, and resulted relevant only in sites with the lowest yields at the zero N rate treatments. Sainz Rozas et al. (2001; 2004) found that delaying N fertilization from sowing to V6 increased N use efficiency because of a reduction in denitrification losses in water-logged conditions, and a reduction in NO_3 leaching in deep sandy soils. We hypothesized that shallow ground water tables could affect N responses by affecting the risk of nutrient losses. However, results showed that delaying the fertilization timing from sowing to V7 had minimum effects, and inconsistent across sites (in some cases higher yield when N was applied at sowing and in others when applied at V7). These results emphasize the need to optimize the amount of N to apply in each specific field rather than the timing of the application.

Water table depth at sowing did not explain yield response differences to N rate, and thus, was not an adequate explanatory variable to express the influence of water table on the yield response to N fertilization. This may have been due to the low variation across sites, as they all had an influencing water table within a narrow depth (Table 1). Yield response differences to N rate across sites were explained mostly by apparent-INS, soil N-NO_3 at sowing, and previous crop.

Cassman et al. (2002) reported that apparent-INS in soils from the United States typically range from 80 to 240 kg N ha^{-1}. Soil N supply has a very high N fertilizer substitution value because of the relatively low recovery efficiency from N rate fertilizer (Cassman et al., 2002) and explained yield variation in zero N rate treatments (Cassman et al., 1996). In our study we also detected a high yield variation in the zero N rate treatments, and they were also positively correlated to apparent-INS ($r = 0.96$; $p<0.01$), which ranged from 80 to 160 kg N ha^{-1}. Similar to Cassman et al. (1996), no correlation between apparent-INS and SOM was found. As opposed to Orcellet et al. (2017) who found a close association between N_{an} and yield in the control treatments (N_{an} CV 25%), we were not able to confirm this association, probably because small N_{an} variation among sites (CV 15%). This low variability in explored N_{an} might be related to similar crop rotations and management practices. Apparent-INS explained site to site grain yield variations in the zero N rate treatments and in the yield response to N rate. Since apparent-INS was a good explanatory variable but is unknown until harvest, developing prediction models for apparent-INS could help on the development of refined N management guidelines.

It is well documented that a differential crop sequence affects the maize yield response to N fertilization (Dobermann et al., 2011; Enrico et al., 2020). Nitrogen dynamics are affected by the decomposition of residues with different

C:N ratios (Gentry et al., 2001) and residue amount (Puntel et al., 2019). Wheat residue has a high C:N ratio, characterized by N immobilization, whereas soybean residue has a low C:N ratio and potentially releasing considerable amounts of N during the next cropping season (Kaboneka et al., 1997). In this study we found higher levels of initial soil N-NO_3 and apparent-INS when predecessor crop was soybean rather than double crop wheat/soybean. This higher N availability resulted in lower yield responses to N rate when soybean was the previous crop.

The most frequent approach to decide N fertilizer needs in the center temperate Argentinean region is using yield response functions to the sum of soil N and fertilizer N as a single measure of N availability, fitted using ordinary least squares (Pagani et al., 2008; Salvagiotti et al., 2011). We also detected the relevance of initial soil N-NO_3 to assist fertilizer recommendations. However, in our study we used linear mixed-effects models that consider that the yield response to N rate varies across environments and use explanatory variables at the environment level to estimate the magnitude of the yield response to N rate. As a result, these types of models are more adequate for N recommendations than traditional empirical models that estimate N fertilizer needs using soil N plus N rate (Coyos et al., 2018). Finally, these models can contribute to the development of improved N recommendation guidelines to aid farmers and advisors when deciding N fertilizer rates.

CONCLUSIONS

Nitrogen fertilization applied at sowing showed similar yield responses to N applied in V7 in environments with influencing water tables that fluctuate within optimum depth. This indicated that optimizing N rate was more relevant than optimizing fertilization timing in maize crops sown in these environments. This response was mainly explained by the capacity of the soil to supply N.

Apparent-INS, soil N-NO_3 at sowing, and previous crop were the most relevant variables for explaining crop yield differential responses to N rate across sites, and may be included in recommendation guidelines when deciding N fertilizer rates.

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FIGURE CAPTIONS

Figure 1. Geographical distribution of experiments within Córdoba Province, Argentina. The smallest bounded areas in the right map are counties (provincial department).

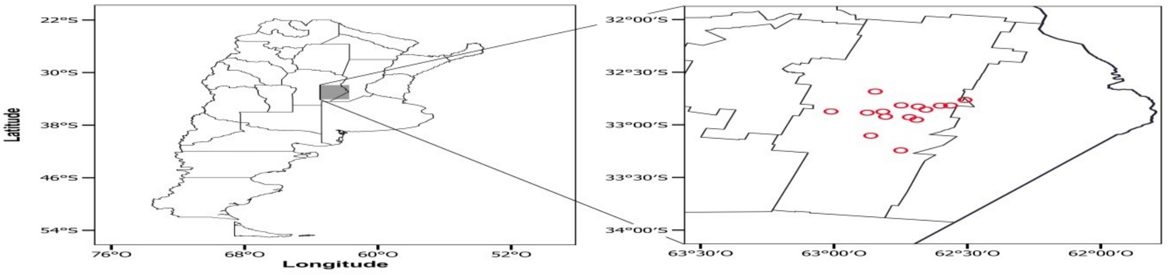

Figure 2. Grain yield for extreme N rate treatments: 0 kg N ha^{-1} rate (red circles) and 240 kg N ha^{-1} rate (blue circles) at each site (**A**). Yield difference between fertilization timings (sowing minus V7) across N rate treatments at each site (**B**). In Figure 2B, the dashed line represents the least significant difference (LSD, $p<0.05$). Sites are ordered based on their yield at the 0 kg N ha^{-1} rate treatment.

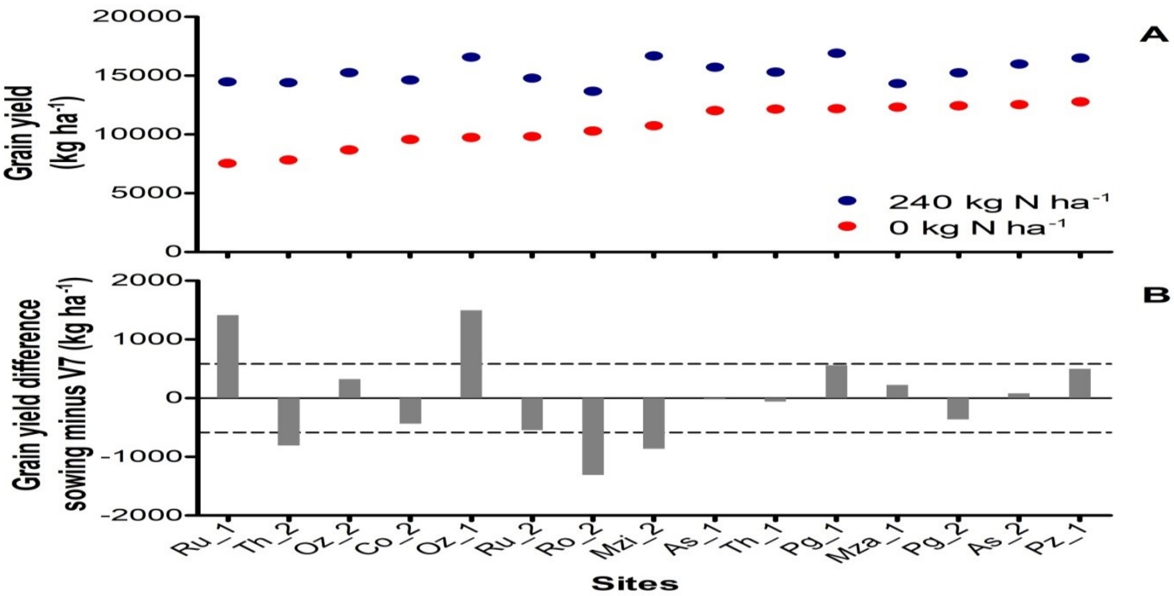

Figure 3. Fitted values obtained by mixed-effects modeling of random intercept and slope in which a site effect is included as a variation around the intercept and an N rate x site interaction effect is included as a variation around the slope (model A). Red line represents the fixed component of N rate for the population of sites. Parameters for equations described for each site are in Suppl. Table S1.

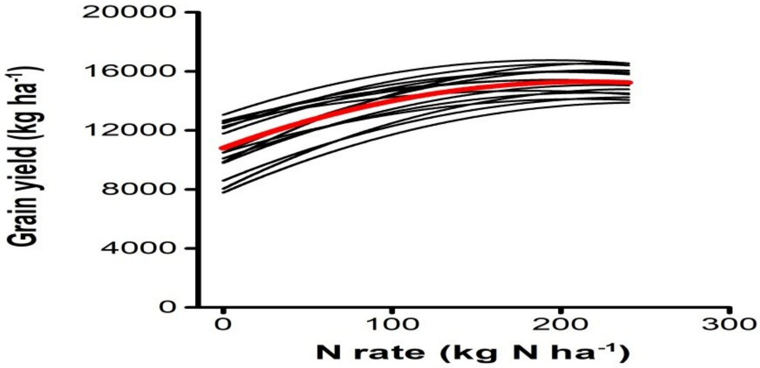

Figure 4. Correlations between parameters β_{0j} and β_{1j} with apparent-INS, soil N-NO$_3$ at sowing, and previous crop (S, soybean as a single crop; W/S, wheat/soybean as a double crop). β_{0j} represents the intercept variation due to site, and β_{1j} represents the linear parameter of the quadratic response of yield versus N rate for each site.

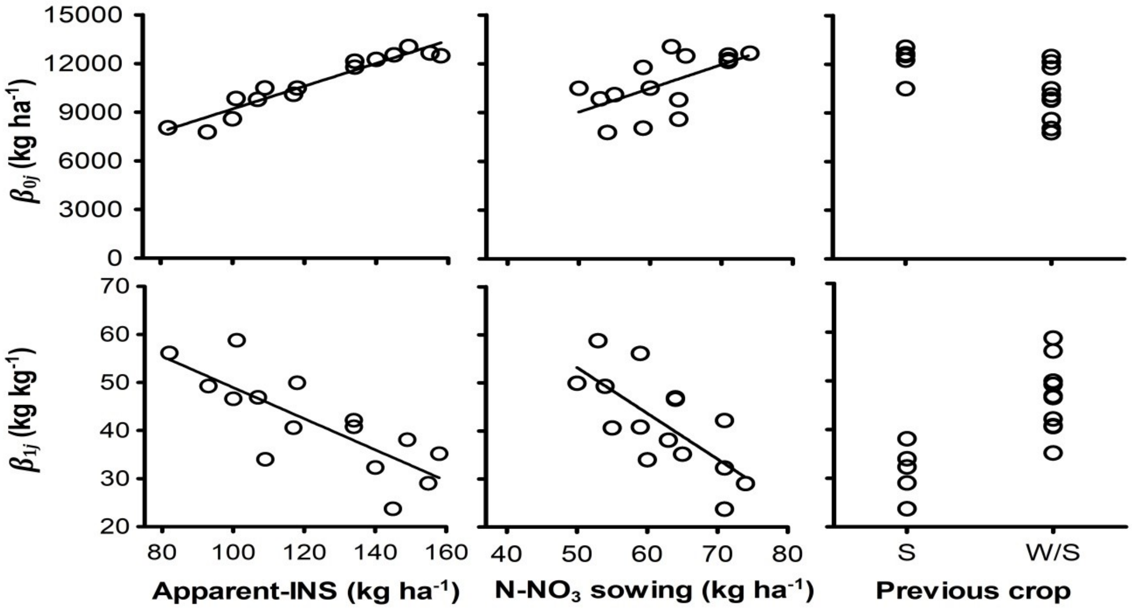

Figure 5. Grain yield response to N rate in each site. Lines reflect the final models B, C, and D, considering the fixed components shown in Table 3 (black line represents model B, blue line represents model C, and green line represents model D).

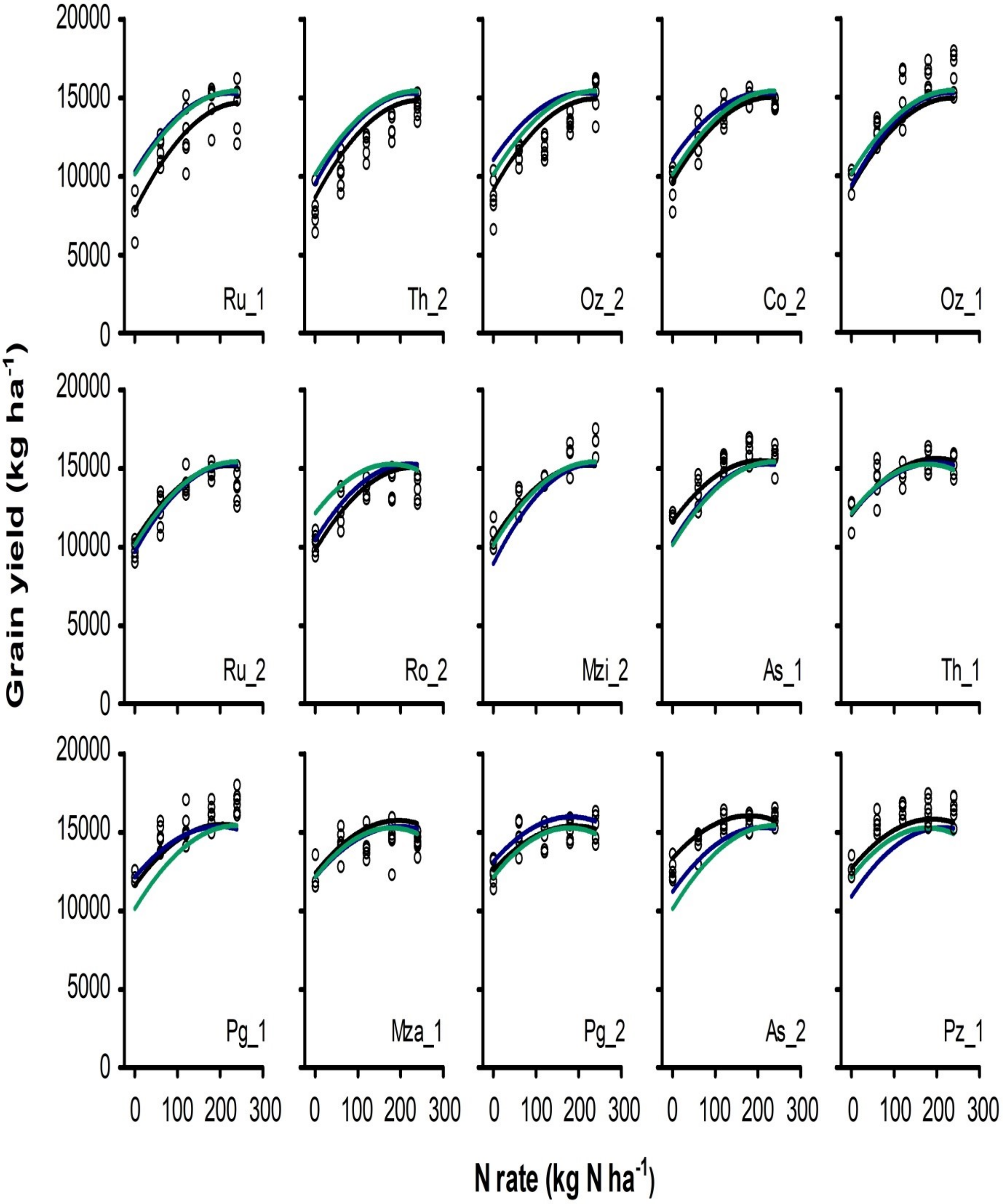

Figure 6. Expected grain yield response to N rate considering different site level explanatory variables. Model B considers three levels of apparent-INS: 80 kg N ha^{-1} (dashed line; Y = 7713 + 55.2 * X – 0.11 * X^2), 120 kg N ha^{-1} (dotted line; Y = 10599 + 42.4 * X – 0.10 * X^2), and 160 kg N ha^{-1} (full line; Y = 13486 + 29.6 * X – 0.08 * X^2). Model C considers three levels of soil N-NO$_3$ at sowing: 50 kg N ha^{-1} (dashed line; Y = 8937 + 54.2 * X – 0.12 * X^2), 60 kg N ha^{-1} (dotted line; Y = 10460 + 43.9 * X – 0.10 * X^2), and 75 kg N ha^{-1} (full line; Y = 12745 + 28.6 * X – 0.08 * X^2). Model D considers previous crop: wheat/soybean (dashed line; Y = 10126 + 44.7 * X – 0.09 * X^2) and soybean (full line; Y = 12150 + 35.0 * X – 0.10 * X^2). Apparent-INS and soil N-NO$_3$ levels are minimum, mean, and maximum based on observed data.

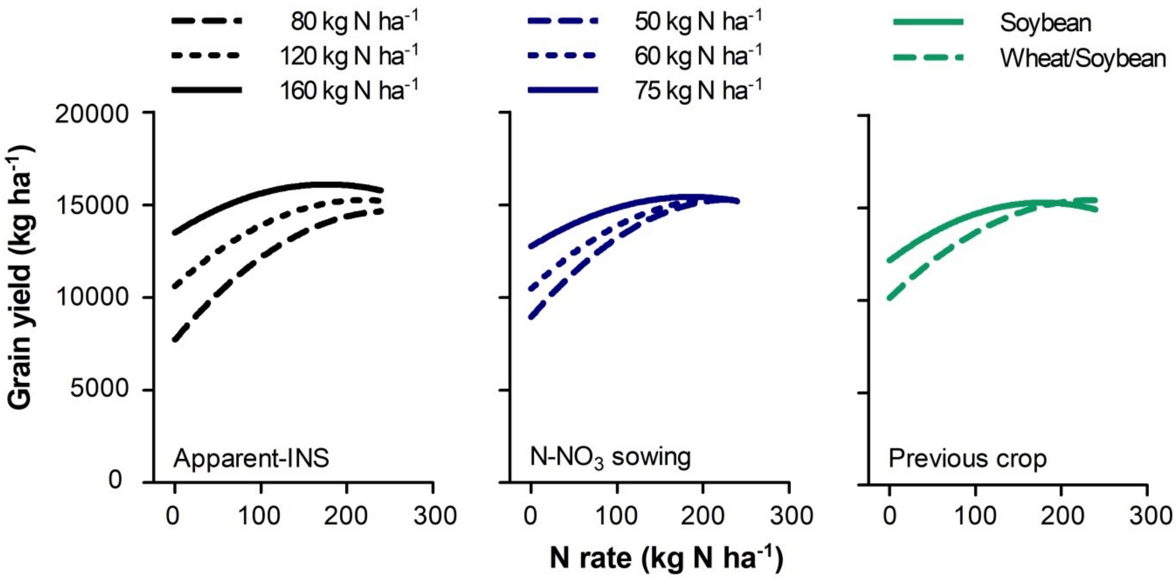

Table 1. Description of the 15 sites were the N experiments were conducted, including site name, soil type and productivity class, sowing date, hybrid, stand density, previous crop, water content (percentage of maximum water holding capacity at sowing), rainfall from sowing to physiological maturity, water table

(sowing - physiological maturity), SOM (soil organic matter), N-NO_3 from surface to 60 cm depth at sowing (N-1), N_{an} (anaerobic nitrogen), P, conductivity, pH, N-NO_3 from surface to 60 cm at V4 (N-2), N-NO_3 from surface to 30 cm depth at V4 (N-3), and apparent-INS (apparent-indigenous N supply). For water table, the range indicated its depth at sowing and at physiological maturity, respectively.

Site	**Soil type**	**Soil class**	**Sowing date**	**Hybrid**	**Stand density**	**Previous crop**	**Water content**	**Rainfall**	**Water table**	**SOM**	**N-1**	**N_{an}**	**Soil P**	**Conductivity**	**pH**	**N-2**	**N-3**	**Apparent-INS**
					pl m^{-2}		%	mm	m	%	kg ha^{-1}	ppm	ppm	mmhos cm^{-1}		kg ha^{-1}	kg ha^{-1}	kg ha^{-1}
Pg_1	Typic Hapludoll	IIc	22 sep	DK7210	7.9	Wheat/soybean	94	498	1.5 - 3.0	2.5	71	40	12	0.10	5.8	40	13	134
Oz_1	Typic Argiudoll	IIc	5 oct	DK7210	8.3	Wheat/soybean	98	488	1.0 - 2.0	2.6	53	48	13	0.09	6.0	63	24	101
Mza_1	Udic Haplustoll	IIc	9 oct	DK7210	7.2	Soybean	98	459	0.7 - 2.0	2.3	71	42	15	0.10	5.9	51	23	145
Pz_1	Typic Argiudoll	IIc	10 oct	DK7210	9.0	Soybean	91	496	1.5 - 3.0	2.4	63	43	8	0.09	6.0	46	21	149
Th_1	Typic Hapludoll	IIc	9 oct	DK7210	8.0	Soybean	93	496	2.0 - 3.0	2.4	71	39	13	0.11	6.0	77	30	140
As_1	Typic Hapludoll	IIc	23 oct	DK7210	7.7	Wheat/soybean	100	490	1.0 - 2.0	2.3	59	39	11	0.08	6.0	60	24	134
Ru_1	Typic Hapludoll	IIc	8 oct	ACA470	7.3	Wheat/soybean	100	474	0.7 - 2.0	2.4	59	40	11	0.10	5.9	50	17	82
Oz_2	Typic Argiudoll	IIc	16 sep	DK7320	7.9	Wheat/soybean	100	407	1.0 - 2.5	2.7	64	50	13	0.10	5.5	55	23	100
As_2	Typic Hapludoll	IIc	17 sep	DK7210	8.7	Wheat/soybean	100	325	1.0 - 2.5	2.7	65	64	17	0.13	5.7	91	33	158
Ro_2	Typic Hapludoll	IIc	19 sep	DK7310	8.1	Soybean	100	407	1.5 - 3.0	2.7	60	50	11	0.10	5.5	62	27	109
Ru_2	Typic Hapludoll	IIc	20 sep	ACA473	7.8	Wheat/soybean	98	427	2.0 - 3.5	2.4	55	41	12	0.10	5.9	53	23	117
Pg_2	Typic Hapludoll	IIc	20 sep	DK7210	8.1	Soybean	100	407	1.0 - 2.5	2.7	74	45	25	0.09	5.3	69	29	155
Mzi	Udic	IIc	5	DK7	8.6	Wheat/s	95	372	2.0	2.	5	4	11	0.10	5	75	33	118

_2	Haplustoll		oct	210		oybean			-3.5	8	0	2			.5			
Co_2	Typic Argiudoll	IIc	9 oct	DK7210	7.3	Wheat/soybean	100	349	1.0-2.5	2.7	64	53	35	0.12	5.6	86	43	107
Th_2	Typic Hapludoll	IIc	6 oct	DK7320	7.6	Wheat/soybean	100	349	1.0-2.5	2.5	54	46	8	0.09	5.6	53	20	93

Table 2. P-value and relative contribution to the total yield variance of each effect for grain yield. Treatments involved five N rates applied at two different timings in 15 sites.

Source of variation	Grain yield	
	p-value	Variance %
Site	<0.001	19.7
N rate	<0.001	57.6
Timing	0.628	<0.1
Site x N rate	<0.001	7.4
Site x Timing	<0.001	3.7
N rate x Timing	<0.001	0.9
Site x N rate x Timing	0.494	0.2
Residual		10.4

Table 3. Summary statistics of different explored models of the potential effect of apparent-INS (model B), soil N-NO_3 at sowing (model C), and previous crop (model D) on grain yield and yield response to N rate. $R^2{}_m$ is the variance explained by fixed effects and $R^2{}_c$ is the variance explained by the entire model. Estimates (± standard error, SE) of fixed effects are provided for each model. In model D, the baseline is

soybean, and the effect of the previous crop represents the double crop wheat-soybean (W/S). See Materials and Methods and Suppl. Table S3 for further details.

		Model B	**Model C**	**Model D**
AIC		7213	7238	7240
R^2_m		0.83	0.37	0.47
R^2_c		0.83	0.90	0.88
Fixed effects			***Estimate and SE***	
Intercept	α_0	1940 ± 492	1322 ± 4866	12150 ± 748
N rate	γ_0	80.8 ± 24.9	105.2 ± 16.1	35.0 ± 3.9
	δ_0	-0.14 ± 0.11	-0.19 ± 0.09	-0.10 ± 0.02
Apparent-INS	α_1	72.2 ± 3.9		
Soil N-NO_3	α_2		152.3 ± 77.7	
Previous crop W/S	α_3			-2024 ± 915
N rate x Apparent-INS	γ_1	-0.3 ± 0.2		
	δ_1	0.0003 ± 0.0008		
N rate x Soil N-NO_3	γ_2		-1.0 ± 0.3	
	δ_2		0.0015 ± 0.0015	
N rate x Previous crop W/S	γ_3			9.7 ± 4.8
	δ_3			0.003 ± 0.02