

Hairy vetch role to mitigate crop yield gap in different yield environments at field level

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ABSTRACT: The spatial variability of soil organic matter, plant water availability, and soil nitrogen (N) availability are drivers of crop response to mineral N fertilizer. The complex interaction of these factors is responsible for within-field corn and wheat yield variability. The hairy vetch (HV) cover crop is an economic, environmentally friendly, and efficient N source capable of conciliating crop yield and soil health. Nevertheless, the HV effects to mitigate yield gap of management zone (MZ) have not yet been documented. This study evaluated the effects of HV and mineral N fertilization, in single or combined input, on alleviating crop yield gap. The study was carried out in two croplands southern Brazil. The experimental design was a complete randomized block in a split plot having MZ (high, medium, and low yield) and N fertilizer rates. Wheat and corn N uptake and grain yield had a quadratic adjustment with N fertilizer input, but there was a significant MZ effect, where low yield zone (LYZ) was less responsive. Consequently, mineral N fertilization as a single input to mitigate the yield gap in this MZ was not efficient. On the other hand, HV increased corn N uptake and grain yield mainly in LYZ compared to MYZ and HYZ. HV fully mitigated the yield gap between MYZ and HYZ. The combined use of HV and mineral N fertilization rate adjusted according to N legume credit and MZ was an efficient strategy to boost yield, favoring soil health and environmental protection.

Keywords: nitrogen, precision agriculture, legume cover crop, conservation agriculture

Introduction

Corn (*Zea mays* L.) and wheat (*Triticum aestivum* L.) are the second and fifth grain crops most produced in Brazil, respectively (CONAB, 2020). Yield of these crops is highly dependent on the level of technology used and nitrogen (N) plant uptake (Raun et al., 2011) with a complex interaction with soil health (Wingeyer et al., 2015) and regular distribution of rainfall during critical phenological stages (Amado et al., 2013). To reach high yields, corn and wheat need a large amount of N that soils generally are not capable of supplying in terms of time and quantities required (Cassman et al., 2002). Consequently, a great proportion of crop N demand is generally supplied by mineral N fertilization that has an important environmental footprint (Tagarakis and Ketterings, 2017). In this scenario, tools to improve N use efficiency are highly demanded to conciliate competitive yields with environmental protection (Lu et al., 2019).

Crop yield within-field variability can be addressed by management zones (MZ) that, combined with in-season crop vegetation indices, can be drivers to fine-tune N fertilization (Peralta et al., 2015; Schwalbert et al., 2018b). MZ can be defined as the homogeneous portion of the field with similar texture and soil depth, organic matter, structure, topography, plant water, and nutrients availability that affect crop yield (Doerge, 1999). Decreasing the N fertilization rate in low yield zones (LYZ) is a logical economic and environmental approach to control N loss (Lu et al., 2019), while improving economic return (Schwalbert et al., 2018a).

Hairy vetch (*Vicia villosa* Roth) (HV) has been used as a legume cover crop due its low C:N ratio

(ranging from 10:1 to 15:1), high biological N fixation ($\approx 100\text{-}150\text{ kg ha}^{-1}$), fast biomass decomposition, and N release (up to 90 % of N release in four weeks after management (Acosta et al., 2011)) and general soil quality improvement (Poffenbarger et al., 2015). The HV biomass production, total N uptake, and C:N ratio can vary across environments and management practices (Finney et al., 2016). Therefore, benefits of legume cover crop should be assessed following the site-specific approach regularly applied in precision agriculture (Ketterings et al., 2015).

The main objective of this study was to investigate the effect of HV cover crop alone or in combination with crop mineral N fertilizer on the increase of plant N uptake and mitigation of within-field grain yield variability.

Materials and Methods

This study comprises the period from 2013 to 2016 continuing the work initially carried out by Schwalbert et al. (2018a) with wheat (2013 to 2014) and followed by this study with corn (2014 to 2016) in the same experimental fields.

Study site

This study was carried out in rainfed fields in the municipality of Carazinho, Rio Grande do Sul State, Brazil, totalizing four year crops. Field 1 is located at 28°19'16" S, 52°42'25" W and altitude 610 m. The study was carried out during the seasons 2014 (wheat) and 2014/2015 (corn). Field 2 is located at 28°19'27" S 52°43'57" W and altitude 610 m. The study was carried

out during 2013 (wheat) and 2015/2016 (corn). The fields were managed under no-till (for more than 10 years) and with adoption of precision agriculture tools (Amado and Santi, 2011) before the start of the experiment. The landscape is classified as rolling-relief subject to runoff and rill erosion associated to the frequent occurrence of heavy rain events. The soil is Typic Hapludox according to Soil Survey Staff (2014), deep, and well drained. The climate, according to the Köppen classification (Alvares et al., 2013), is Cfa. January is the warmest month with an average temperature of 24.6 °C and June is the coldest month with an average temperature of 12.9 °C. Rainfall is evenly distributed throughout the year with volume ranging from 1,500 to 1,750 mm (Schwalbert et al., 2018a).

Soil and plant attributes used for zones delineation

The attributes used to define MZ were apparent soil electrical conductivity (ECa) at two depths (0-0.30 m and 0-0.90 m) measured 30 days before planting wheat (*Triticum aestivum* L.). The soil electrical conductivity sensor was pulled across the field in a series of parallel transects spaced of 20 m intervals, as recommend by Farahani and Flynn (2007). Selected data on corn yields data were obtained from 2011/2012 for Field 1 and 2012/2013 for Field 2. The yield data were filtered using Yield Editor Software (Sudduth and Drummond, 2007). Finally, data on terrain elevation were obtained with GPS with signal correction, coupled to the harvester.

All ancillary data were projected to a metric coordinate system (WGS 1984 UTM Zone 21S) using the *rgdal* package (Bivand et al., 2014) and interpolated in raster maps with a 5 × 5 m grid size using ordinary kriging interpolation based on the *gstat* package (Pebesma, 2004), both implemented in R software (R Core Team, version 3.1.3). In addition, data from each map were exported in the text format using the grid center coordinates to ensure that the location of the data point for each layer was the same to allow overlaying the attributes.

The data was submitted to the principal component analysis (PCA), performed in R software (R Core Team, version 3.1.3) using the *psych* package (Revelle, 2015). After, the first two components (PC1 and PC2) with the highest eigenvalues were extracted to be used in the cluster analysis through the fuzzy c-means algorithm with the *e1071* package (Meyer et al., 2014). The optimal MZ numbers were determined using two indexes: the Normalized Classification Entropy (NCE) that represents the zone homogeneity and the Fuzzy Performance Index (FPI) that represents a measure of the distinction between the groups (Odeh et al., 1992). The optimal MZ numbers for each field were determined when the FPI and NCE reached a minimum value. Therefore, we delimited three MZ numbers, classified in low (LYZ), medium (MYZ) and high yield zone (HYZ) for each field.

Treatments, experimental design, and data collection

The experimental design in the corn study was a complete randomized block with three replicates located within each MZ, which were placed in agreement with the MZ established by Schwalbert et al. (2018a) for the wheat study. The experimental unit had 32 m² with dimensions of 8 m long by 4 m wide. In the year prior to this study in both fields, wheat was grown during the winter and soybean (*Glycine max* L.) during the summer growing seasons. HV was sown in Apr on soybean residues (Table 1) using a commercial winter planter. The HV seed rate was 20 kg ha⁻¹, marking the beginning of our corn experiment. In the treatment without HV, weeds were scraped with manual brush leaving the plots with bare soil. In the treatments with HV, aboveground biomass production and total aboveground N content were evaluated through five sub-samples in a known area (0.25 m²) in the pre-flowering stage in Sept. One day after, HV termination was made by applying herbicide (2000 g ha⁻¹ a.i. glyphosate) followed by a knife-roller to leave HV residues in a uniform lay on soil surface.

Corn was sown 15 days after HV termination, using a commercial no-till seeder. The Pioneer 30F53YH hybrid was used and the plant population was set to 64 thousand plants ha⁻¹ in both fields. Fertilization started at sowing at 28 kg ha⁻¹ of N, 70 kg ha⁻¹ of P₂O₅, and 70 kg ha⁻¹ of K₂O in both fields. Weeds, diseases, and insect pests were controlled adequately during crop growing season.

The treatments comprised five mineral N fertilizer rates in the presence of HV residues and HV absence (non-HV) in the three MZ, resulting in 30 plots. The mineral N fertilizer rates (0, 60, 120, 180, 240 kg ha⁻¹) were manually broadcast on soil surface applied in a single application at V4 corn growth stage following the Hanway Scale (Hanway, 1966), using urea as the N mineral fertilizer source.

Corn N uptake was evaluated at flowering growth stages (Hanway, 1966) in a known area (1 m²) totalizing six plants per plot. The whole aboveground corn plant was collected, dried at forced-air-drying system at 75 °C until constant weight and then ground to evaluate the plant N content by the micro-Kjeldahl wet combustion (Bremner and Mulvaney, 1982). The same procedure was used to HV.

To quantify corn grain yield, three samples of 1 m² were manually collected totalizing 18 plants per plot and the grain moisture was adjusted to 130 g kg⁻¹.

The corn N uptake derived from HV was estimated for each mineral N fertilizer rate by subtracting the corn N uptake in the treatment with HV from the treatment without HV.

The N uptake effect (%) and grain yield effect (%) were estimated assuming as reference treatment the plant N uptake and grain yield of MYZ, without HV and with mineral N fertilization of 80 and 120 kg ha⁻¹ for wheat and corn, respectively. The mineral N fertilization

Table 1 – Soil and hairy vetch properties and dates of operations for Field 1 and Field 2.

Variables	Field 1 (2014/2015)			Field 2 (2015/2016)		
	LYZ ⁷	MYZ	HYZ	LYZ	MYZ	HYZ
Soil properties ¹						
P (mg kg ⁻¹)	4.2	12.4	13.8	12.2	15.3	16.2
K ⁺ (mg kg ⁻¹)	118	156	189	115	134	142
Ca ⁺⁺ (cmol _c dm ⁻³)	6.3	6.5	6.4	3.5	5.1	6.2
Mg ⁺⁺ (cmol _c dm ⁻³)	2.9	2.8	2.5	1.2	1.7	2.3
pH water	5.4	5.4	5.3	4.6	4.9	5.4
SOM (g kg ⁻¹) ²	24	31	32	23	29	32
Clay (g kg ⁻¹)	500	680	640	420	590	600
Slope (%)	8.2	3.5	5.0	6.0	3.3	3.8
ECa 0-0.3 m (mS m ⁻¹) ³	5.8	7.7	8.0	5.1	6.5	8.0
ECa 0-0.9 m (mS m ⁻¹)	68.0	90.0	106.0	60.0	73.0	91.0
Hairy vetch properties						
Dry aboveground biomass (kg ha ⁻¹)	5332 c ⁶	5589 b	5834 a	4234 c	4563 b	4724 a
N content (N kg ha ⁻¹)	205 b	215 a	212 a	188 b	199 a	199 a
Field operations						
Hairy vetch seeding		15/04			03/04	
Hairy vetch biomass sampling		15/09			02/09	
Corn planting		28/09			17/09	
N application (V4) ⁴		30/10			17/09	
Corn biomass sampling (VT) ⁵		21/12			16/12	
Corn manual harvest		29/02			18/02	

¹Soil samples collected from 0 to 0.20 m depth; ²Soil organic matter; ³Soil apparent electric conductivity; ⁴Fourth leaf; ⁵Flowering growth stages; ⁶For each field and variable, different letters indicate significant differences between MZ ($p < 0.05$); ⁷LYZ = low yield zone; MYZ = medium yield zone; HYZ = high yield zone.

rates (80 and 120 kg ha⁻¹) were similar to inputs regularly used by farmers in southern Brazil. All the treatments were relativized to reference according to the Eq. (1):

$$\frac{\text{Treatment investigated} - \text{Treatment reference}}{\text{Treatment reference}} \times 100 \quad (1)$$

The wheat and corn yield gap were estimated to three scenarios: a) mineral N fertilizer rates with non-HV, b) with HV without mineral N fertilizer, and c) combined HV with non-limited N rate (120, 180 and 240 kg ha⁻¹).

Weather data was obtained from an INMET (National Meteorological Institute) meteorological station (INMET, 2020), located in the municipality of Passo Fundo, Rio Grande do Sul State, Brazil, 35 km distant from the experimental area.

The statistical analysis was performed using R software (R Core Team, version 3.1.3). To test the significance of the treatments and their interactions and compare treatments within each MZ, including the N fertilizer rate \times MZ interaction and the presence or absence of HV as cover crop, one mixed linear model (MLM) of ANOVA was adjusted for corn grain yield and plant N uptake.

HV biomass production and N uptake were analyzed without transformation and the differences between the means were compared by the Least Significant Differences (LSD) with the Tukey-Kramer test at the $p < 0.05$ significance level. When there was interaction between MZ, HV as cover crop, and mineral N fertilizer rates, the linear regression analysis was performed independently for each MZ.

Results and Discussion

Effects of treatments and their interactions

A significant ($p < 0.05$) three-way ANOVA interaction was not observed for any variable investigated. However, all the two-way ANOVA interactions were significant for corn grain yield and plant N uptake. Thus, response to mineral N fertilization differs according to MZ and HV-treatments.

Weather conditions

In general, the weather conditions were favorable to the corn crop in both seasons. Field 1 had lower daily average temperatures and cold nights in the period after flowering and better rainfall distribution during the plant reproductive stage compared to Field 2. In Field 2, a high rainfall event (85 mm) was noted two days after mineral N fertilization application. Huang et al. (2017) reported that few events of heavy rainfall can cause high N loss in corn crops.

Plant nitrogen uptake

In Field 1, the corn N uptake in non-HV treatments ranged from 148 to 224 kg ha⁻¹, while in HV-treatments, it ranged from 222 to 272 kg ha⁻¹ (Figure 1A). Moreover, in Field 2, these values ranged from 115 to 184 kg ha⁻¹ for non-HV treatments and from 176 to 221 kg ha⁻¹ in HV-treatments (Figure 1A). These two fields received the same range of mineral N fertilizer (0 to 240 kg ha⁻¹);

however, the larger range of corn N uptake in Field 1 compared to Field 2 was probably due to better rainfall distribution (growing season 2014/15) with a higher amount of rain after the corn flowering stage period, responsible for one-third of total N corn uptake (Bender et al., 2013).

In both fields, corn N uptake was higher in HV-treatments compared to non-HV treatments, regardless of the mineral N fertilizer rate applied (Figure 1A). Corn N uptake increased linearly (HV-treatments) or followed second-order polynomial equations (non-HV treatments) in response to the N fertilizer rates input (Figure 1A). Above 120 kg N ha⁻¹ of mineral N fertilizer rate, no significant increases in corn N uptake was observed for the non-HV treatment in Field 1 (Figure 1A). Moreover, the non-HV treatment with 120 kg N ha⁻¹ showed corn N uptake equivalence with the HV-treatment without mineral N fertilization (Figure 1A). This trend was observed for both fields.

In both fields, HV increased corn N uptake (74 kg N ha⁻¹ in Field 1 and 61 kg N ha⁻¹ in Field 2) decreasing its contribution in N plant nutrition as mineral N fertilization rates increased (Figure 1A). The results agree with Hargrove (1986) and Acosta et al. (2011) who reported a substitutive corn N nutrition of legume N-derived by mineral fertilizer N-derived. This trend is not necessarily a negative process since the legume N-derived main destination could be restoring the total N soil stock (Acosta et al., 2011; Seo et al., 2006) improving N availability to the plant in the long run.

The apparent soil N availability was estimated based on the crop N uptake of non-HV without topdressing N fertilization treatment, disregarding start N fertilization (28 kg ha⁻¹ N). The apparent soil N availability during the corn season was 120 and 87 kg ha⁻¹ for Field 1 and Field 2, respectively (Figure 1A) and the apparent soil N availability during the wheat season was 29 and 35 kg ha⁻¹ for the same fields (Figure 1C). Crop difference in soil N availability could be associated to weather conditions since wheat is grown under low temperatures (winter - June with average 12.9 °C) and corn under higher temperatures (summer - Jan with average 24.6 °C) that affect the soil biological activity and consequently N mineralization. Analyzing the corn N plant nutrition results, the apparent HV N-derived accounts for approximately 40 % while the apparent soil N-derived accounts for 60 % of total plant N uptake for both fields without mineral N supply.

The positive effect of HV cover crop on corn N nutrition status can also be assessed analyzing the curves of mineral N fertilization response (Figure 1A). Regardless of the mineral N fertilizer rate in non-HV treatments, the corn N uptake was always lower than in HV-treatments with the same N fertilization rate. Acosta et al. (2011) evaluated corn N uptake and reported a synergism between the organic (HV) and mineral N (urea) sources probably due to the distinct temporal pattern of N release from these sources, resulting in a better

synchronism with crop demands (Hadas et al., 2002; Crews and Peoples, 2005; Mahama et al., 2016). Besides N contribution of the legume, Hargrove (1986) reported that the rotation effect should be also considered, when legumes are used as cover crops. The improvement in soil quality linked to soil aggregates, soil moisture, biological activity, and better environment to corn root growth provided by HV mulch should be considered (Frye et al., 1985; Utomo et al., 1990) since it may increase plant N uptake. During field operations, HV treatments showed high soil moisture, more macroaggregates, and colder temperature than non-HV (data not shown). These observations agree with SARE (2007) regarding the role of HV as soil conditioner increasing macroaggregates, macro porosity, water infiltration, aggregate stability and decreasing runoff, creating a loose and friable topsoil favorable for corn root growth.

When N sources were combined, HV as cover crop and mineral N fertilization, we reported the highest corn N uptake in both fields, reaching 272 and 221 kg ha⁻¹ for Field 1 and Field 2, respectively (Figure 1A). The N fertilization program primarily aims to increase corn N uptake to improve the plant nutritional status. The combination of different sources of N supply was an efficient strategy to ensure high corn N uptake necessary to meet the high yield potential of modern genetic material.

LYZ and MYZ had higher effects of HV cover crop in relative increase of corn N uptake (Figure 2A). These increases were 23 and 27 % in Field 1; 29 and 26 % in Field 2, for LYZ and MYZ, respectively. While, these increases were 20 and 17 % for the same fields taking into account non-HV treatment as the reference in HYZ (Figure 2A). This effect of HV cover crop, mainly in LYZ, could be attributed to increase N supply and enhancement of synchronism with plant demand (Crews and Peoples, 2005), runoff control and overall soil health improvement, since the HV N-derived input in LYZ was lower than in other MZ in both fields (Table 1). In MYZ, corn N uptake in the HV treatments were higher than HYZ non-HV treatments in both fields (Figure 2A). These results highlight the HV potential to mitigate the YZ effect on plant N nutrition.

Management zone effect on plant N uptake

The MZ effect is presented in Figure 1B (corn) and C (wheat). In LYZ, in both fields, corn, and wheat had no increase or even a decrease in N uptake when N fertilizer rate exceeded 120 kg ha⁻¹ and 80 kg ha⁻¹, respectively (Figures 1B and 1C). Therefore, the strategy of applying high mineral N fertilizer rates to increase crop yield in LYZ can increase environmental impact, since the corn (Figure 1B) and wheat (Figure 1C), since N uptake reached a plateau with middle N fertilizer rate. Khosla et al. (2008) reported that corn in LYZ had the lowest plant N uptake among the zones in a large range of N fertilizer rate investigated.

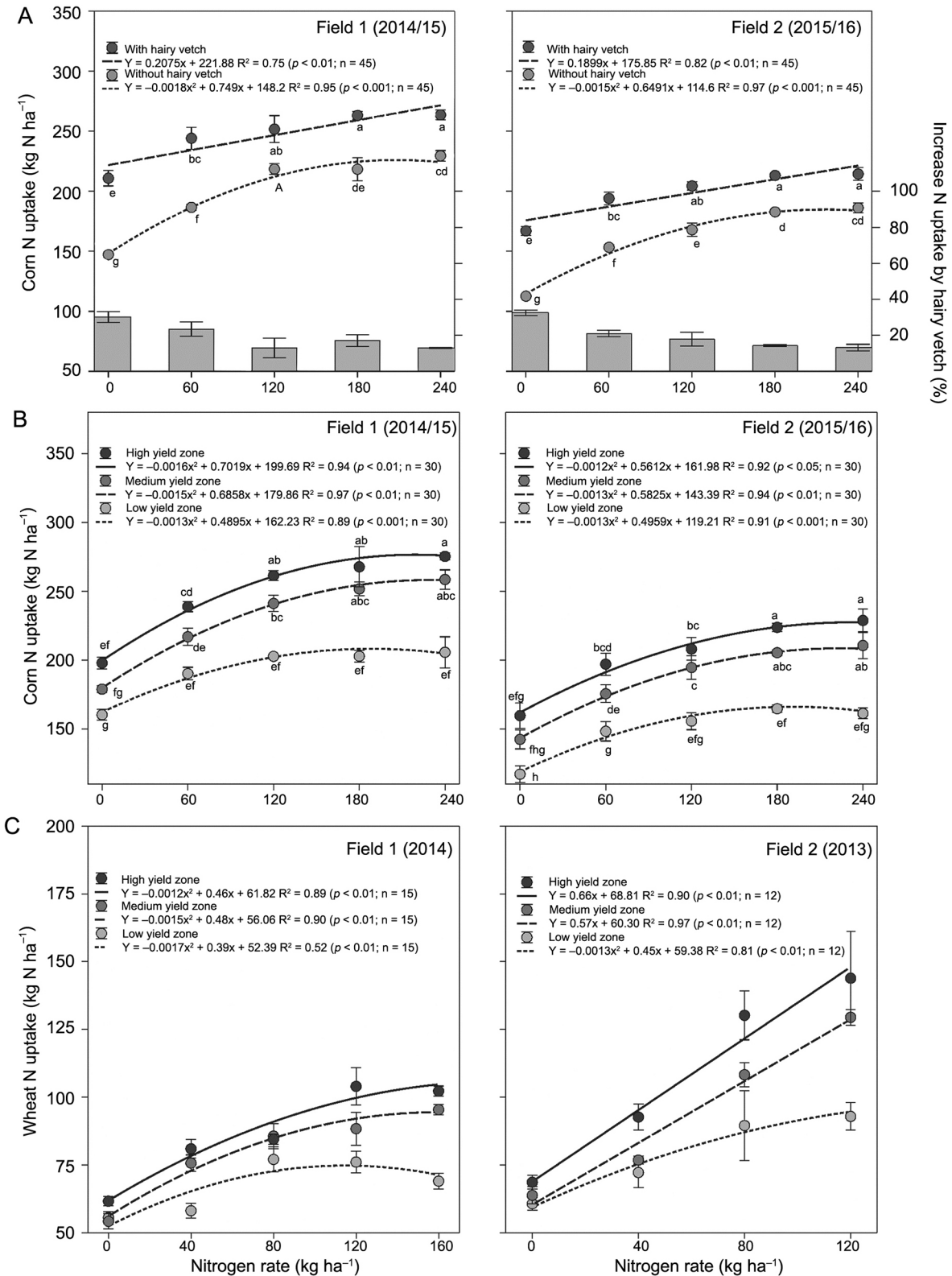


Figure 1 – Crop nitrogen uptake. A) Corn nitrogen uptake affected by mineral nitrogen fertilizer rate with and without hairy vetch as winter cover crop; B) Corn nitrogen uptake influenced by mineral nitrogen fertilizer rates in the management zones; C) Wheat nitrogen uptake influenced by mineral nitrogen fertilizer rates in the management zones (adapted from Schwalbert et al. (2018a)). Data followed by the same letter within fields are not significantly different ($p < 0.05$).

In our study, LYZ with 180 kg ha⁻¹ of mineral N fertilizer rate had the equivalence of corn N uptake of HYZ with very low N rate (13 and 8 kg ha⁻¹ of N fertilization input for Field 1 and Field 2, respectively) (Figure 1B). Likewise, LYZ with 120 kg ha⁻¹ had the equivalence of wheat N uptake of HYZ with 25 to 30 % of the N rate (30 and 39 kg ha⁻¹ of N fertilization input for Field 1 and Field 2, respectively) (Figure 1C). HYZ with high N fertilization rate (240 and 120 kg N ha⁻¹ for corn and wheat, respectively) had the highest corn N uptake of 276 kg ha⁻¹ and 227 kg ha⁻¹ in Field 1 and Field 2, respectively (Figure 1B), while wheat N uptake of 100 and 148 kg ha⁻¹ in Field 1 and Field 2, respectively (Figure 1C). The higher wheat N uptake in Field 2 was associated to better weather condition compared to Field 1 during the wheat season (Schwalbert et al., 2018a). For corn, heavy precipitation right after N application in Field 2 probably increased N losses through leaching and runoff as compared to Field 1 (Huang et al., 2017).

Peralta et al. (2015) and Maestrini and Basso (2018) reported that high-water availability was a crucial factor for greater plant N uptake in HYZ in relation to other MZ. In our study, LYZ had the highest slope, averaging 8 and 6 % for Field 1 and Field 2, respectively (Table 1) which favored runoff compared to other MZ positioned with gentler slope. Khosla et al. (2008) reported the strong relationship between soil water dynamics, affected by topographic factors, with plant nutrient uptake and crop yield.

Corn N uptake in non-HV treatments was 31 and 43 % higher in HYZ, compared to LYZ, for Field 1 and Field 2, respectively (Figure 2A). Higher crop N uptake in HYZ can also be attributed to higher SOM, physico-hydric attributes that favor infiltration and plant water availability (Amado and Santi, 2011). Roberts et al. (2012) reported relevance of topographic attributes to MZ delineation that drives preferential flow, runoff, and erosion (Schwalbert et al., 2018b). The depleted SOM and low clay contents in LYZ compared to HYZ (Table 1) supports the differences reported in plant N uptake by MZ (Figure 2A).

Crop yield

In agreement with the results reported on plant N uptake (Figures 1B and 1C), the corn and wheat grain yield responses to mineral N fertilizer rates followed a quadratic polynomial adjustment regardless of the MZ investigated (Figures 3B and 3C). In addition, the HV cover crop × mineral N fertilization had quadratic adjustments to corn yield (Figure 3A).

Effect of hairy vetch cover crop

The effect of HV on corn yield under a range of mineral N fertilizer rates is shown in Figure 3A. In both fields, the highest HV contribution to grain yield was observed in the absence of mineral N fertilization, decreasing its

contribution as the N fertilizer rate increased (Figure 3A). The same trend was observed with corn N uptake (Figure 1A). In both fields and over all N fertilizer rates used, there was a positive effect of HV-treatments in corn yield compared to non-HV treatments (Figure 3A). Moreover, in the HV-treatments and no mineral N fertilizer, corn grain yield was equivalent to that obtained with up to 240 kg ha⁻¹ of N for Field 1 and 120 kg ha⁻¹ of N for Field 2 with non-HV treatments (Figure 3A). These results were linked to better weather conditions for corn growth. Therefore, the combination of different N sources (organic and mineral) was more efficient to increase corn yield than their use isolated.

Management zone effect in corn and wheat yield

In Field 1, the HYZ, without topdressing N fertilization, had corn yields of 6 and 11 % higher than the MYZ and LYZ, respectively (Figure 3B). Similarly, in Field 2, HYZ had 5 and 21 % higher corn yields than MYZ and LYZ, respectively (Figure 3B). Moreover, in Field 1, HYZ had wheat yields of 7 and 20 % higher than MYZ and LYZ, respectively, without topdressing N fertilization (Figure 3C). In Field 2, HYZ had wheat yields of 45 and 70 % higher (Figure 3C). These data on crop yield support the accuracy of MZ delineation in this study based on data on overlaying ECa, corn yield, and terrain elevation.

In both fields, none of mineral N fertilization rates applied in LYZ achieved comparable corn yield in HYZ with the same N fertilizer rate (Figure 3B). Moreover, in Field 2, any mineral N fertilizer rate applied in LYZ reached the corn yield obtained in MYZ and HYZ (Figure 3B). In Field 1, LYZ with N fertilization of 180 kg ha⁻¹ reached corn yields equivalent to MYZ with 35 kg ha⁻¹ and HYZ without N fertilization (Figure 3B). However, in Field 1, LYZ with N fertilization of 80 kg ha⁻¹ reached wheat yields equivalent to MYZ with 50 kg ha⁻¹ and HYZ with 25 kg ha⁻¹ (Figure 3C). Moreover, as expected for all MZ investigated, there was a quadratic adjustment of corn and wheat yield to mineral N fertilizer rates (Figures 3B and 3C), although there was relevant difference in maximum yield attainable among the MZ.

In Field 1, which had better rainfall distribution and higher corn yield, the three MZ had noticeable differences among them (Figure 3B). While in Field 2, which underwent water stress and lower corn yield, MYZ and HYZ were similar and both different from LYZ (Figure 3B). In Field 2, which had higher wheat yield, the same difference between the MZ effects was observed (Figure 3C). These results suggest an influence of weather (rainfall distribution and plant water availability) on MZ, as HYZ and MYZ had more similarity under water stress and more dissimilarity under favorable rainfall distribution. In addition, LYZ was distinguishable from the other MZ, regardless the rainfall distribution and the presence of abiotic stress. These results are in accordance with Khosla et al. (2008) and Roberts et al. (2012).

The role of hairy vetch and N fertilization to mitigate grain yield gap of varying yield environments

The role of HV as cover crop to mitigate the corn yield gap between MZ is shown in Figure 2B. For the average N fertilizer rates, the HV-treatments had higher corn yields than in non-HV treatments, regardless of MZ. Moreover, for Field 1, on the average N fertilizer rates, the non-HV treatments had the corn yield sequence: LYZ < MYZ < HYZ, with a difference of 1.1 t ha⁻¹ between each other, while in Field 2, LYZ was lower than the other MZ, but without difference between MYZ and HYZ (Figure 2B).

In the HV-treatments, in Field 1, the corn yield in LYZ was 1.7 to 2.3 t ha⁻¹ lower than MYZ and HYZ, respectively (Figure 2B). Moreover, these results for corn yield agree with plant N uptake (Figure 2A). The contribution of HV as cover crop to mitigate corn yield gap is demonstrated by the lack of yield difference between MYZ with HV and HYZ with or without HV (Figure 2B).

The yield gap crops associated to N uptake is presented in Figures 4A to 4D. Figures 4A and 4B show that the relation of corn and the wheat N uptake

was linear to grain yield ($R^2 = 0.85$, $p < 0.05$; $R^2 = 0.90$, $p < 0.05$, for wheat and corn, respectively), considering only non-HV treatments. For both grain crops, the mineral N fertilizer rate alone was not sufficient for LYZ to reach comparable values to yields obtained in the reference (plant N uptake and grain yield of MYZ, without HV and with mineral N fertilization of 80 and 120 kg ha⁻¹ to wheat and corn, respectively), even under higher N rates (160 and 240 kg ha⁻¹ to wheat and corn, respectively) (Figures 4A and 4B). In this case, wheat yield in LYZ ranged between 5 and 48 % lower than the reference (Figure 4A), while for corn, this range was 9 to 26 % lower than the reference (Figure 4B). Moreover, the best relative gain yields of both grain crops were obtained in HYZ, N rate of 120 kg ha⁻¹ or over, which surpassed the referential within the range from 15 to 35 % for wheat (Figure 4A) and within the range from 4 to 13 % for corn (Figure 4B).

In Figure 4C, the HV effect as cover crop without corn N fertilization in relation to the agroecological system show that, for LYZ, the use of HV resulted in a yield gap ranging of -15 to -10 % in comparison with the reference. This result was linked to insufficient plant N uptake (ranging from -19 to -15 %) (Figure 4C). A similar

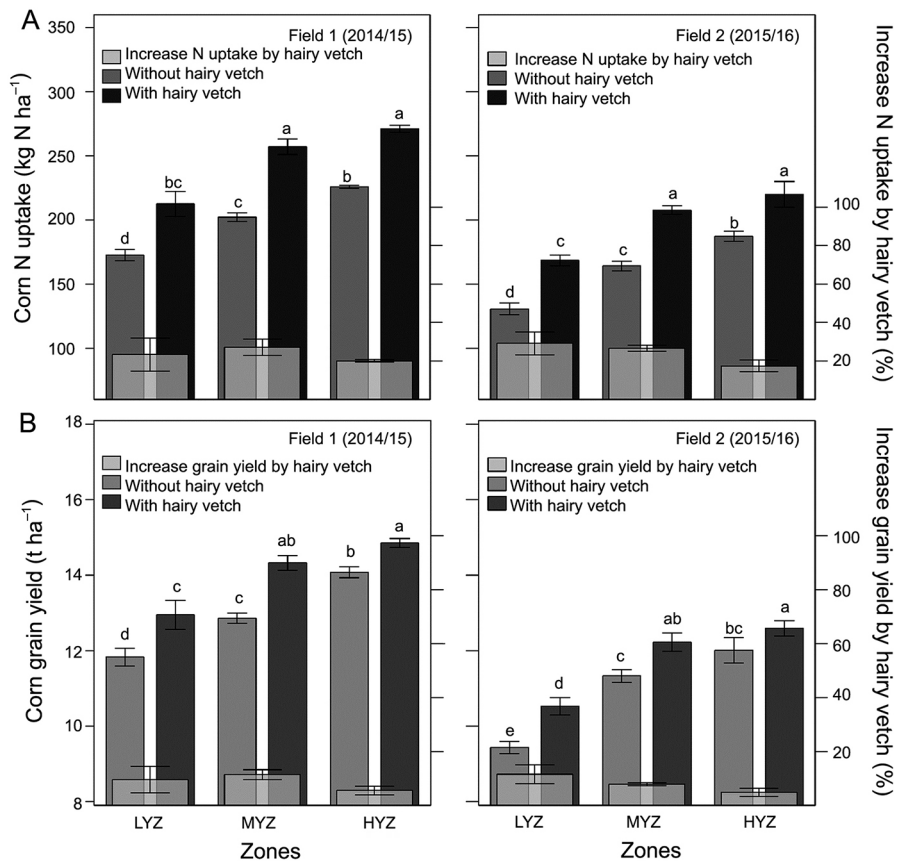


Figure 2 – Corn N uptake (A) and corn grain yield (B) affected by hairy vetch as winter cover crop for Field 1 and Field 2. LYZ = low yield zone, MYZ = medium yield zone and HYZ = high yield zone. Values followed by the same letter within fields are not significantly different ($p < 0.05$).

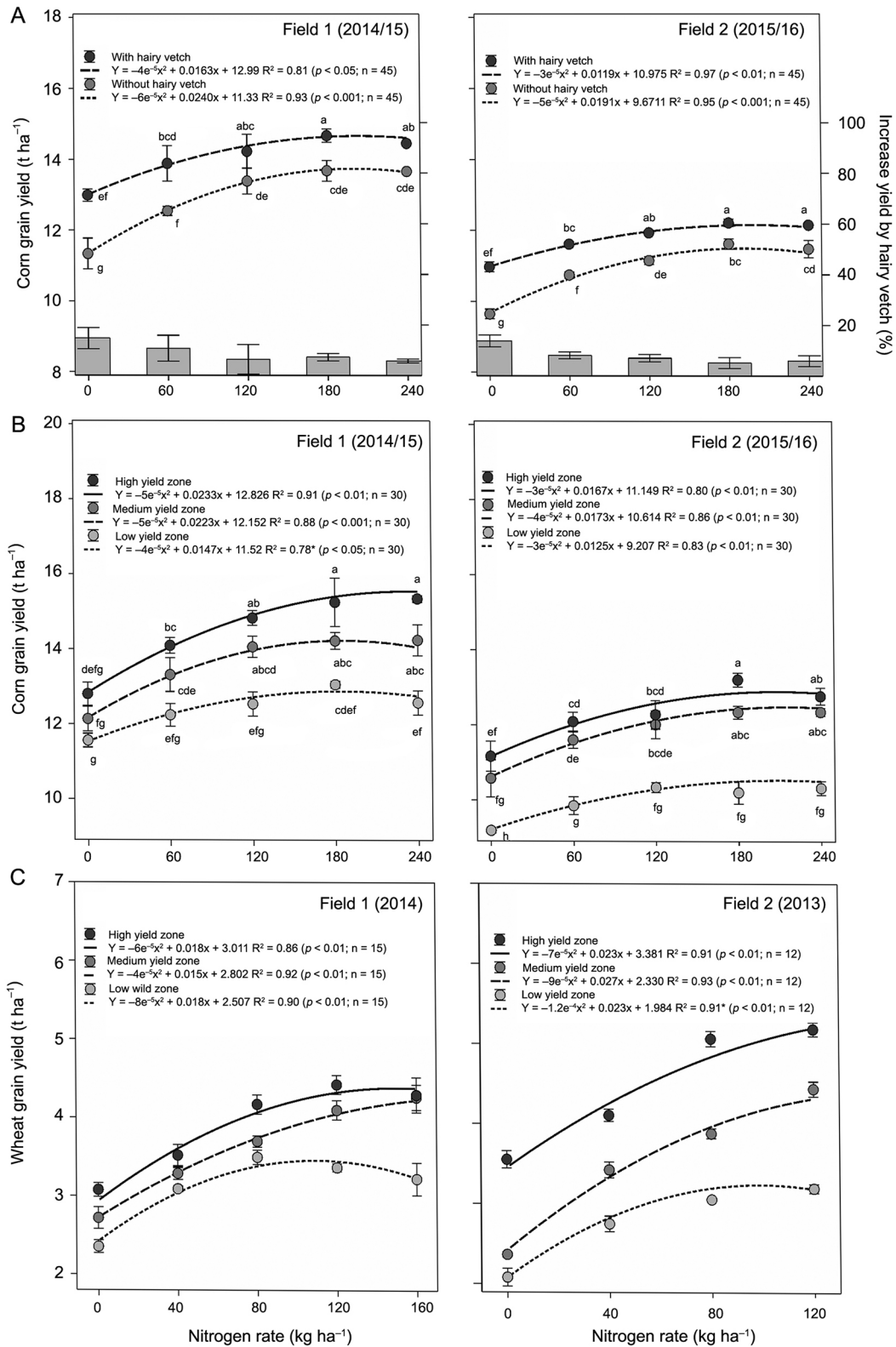


Figure 3 – Crop grain yield. A) Corn grain yield influenced by mineral nitrogen fertilizer rates with and without hairy vetch as winter cover crop; B) Corn grain yield influenced by mineral nitrogen fertilizer rates in the different management zones; C) Wheat grain yield influenced by mineral nitrogen fertilizer rates in the different management zones (adapted from Schwalbert et al. (2018a)). Data followed by the same letter within fields are not significantly different ($p < 0.05$).

trend was observed in MYZ with a yield gap ranging from -4 to -2 % associated to the N uptake effect ranging from -2 to 0 % (Figure 4C). In HYZ, there was no yield gap (-1 and 1 %) compared to the reference, supported by N uptake ranging from 7 to 10 % (Figure 4C).

Figure 4D shows the effect of the combination of HV and non-limited mineral N fertilizer rates (ranging from 120 to 240 kg ha⁻¹) on corn yield. The corn N uptake had a strong relationship with yield ($R^2 = 0.91$, $p < 0.05$). In general, corn yield was boosted by the combination of the cover crop and mineral N fertilization sources. In LYZ, the corn N uptake reaches similar values (HV + 120 kg ha⁻¹) or even slightly

higher (2 to 5 % in HV + 240 kg ha⁻¹ and HV + 180 kg ha⁻¹, respectively) than in the reference. Regarding corn yield gap, the values varied from -8 to -1 % in LYZ. Compared to other strategies (HV or mineral N fertilization) in single use, the combination of N sources was the most efficient. Moreover, MYZ had a corn N uptake ranging from 21 to 33 % leading to a yield gain from 6 to 10 % compared to the reference. Therefore, the yield gap of MYZ in relation to HYZ was almost fully mitigated. Finally, as expected, the best results were obtained in HYZ, with a corn N uptake gain ranging between 26 and 38 % compared to the reference, resulting in a yield gain from 8 to 15 %.

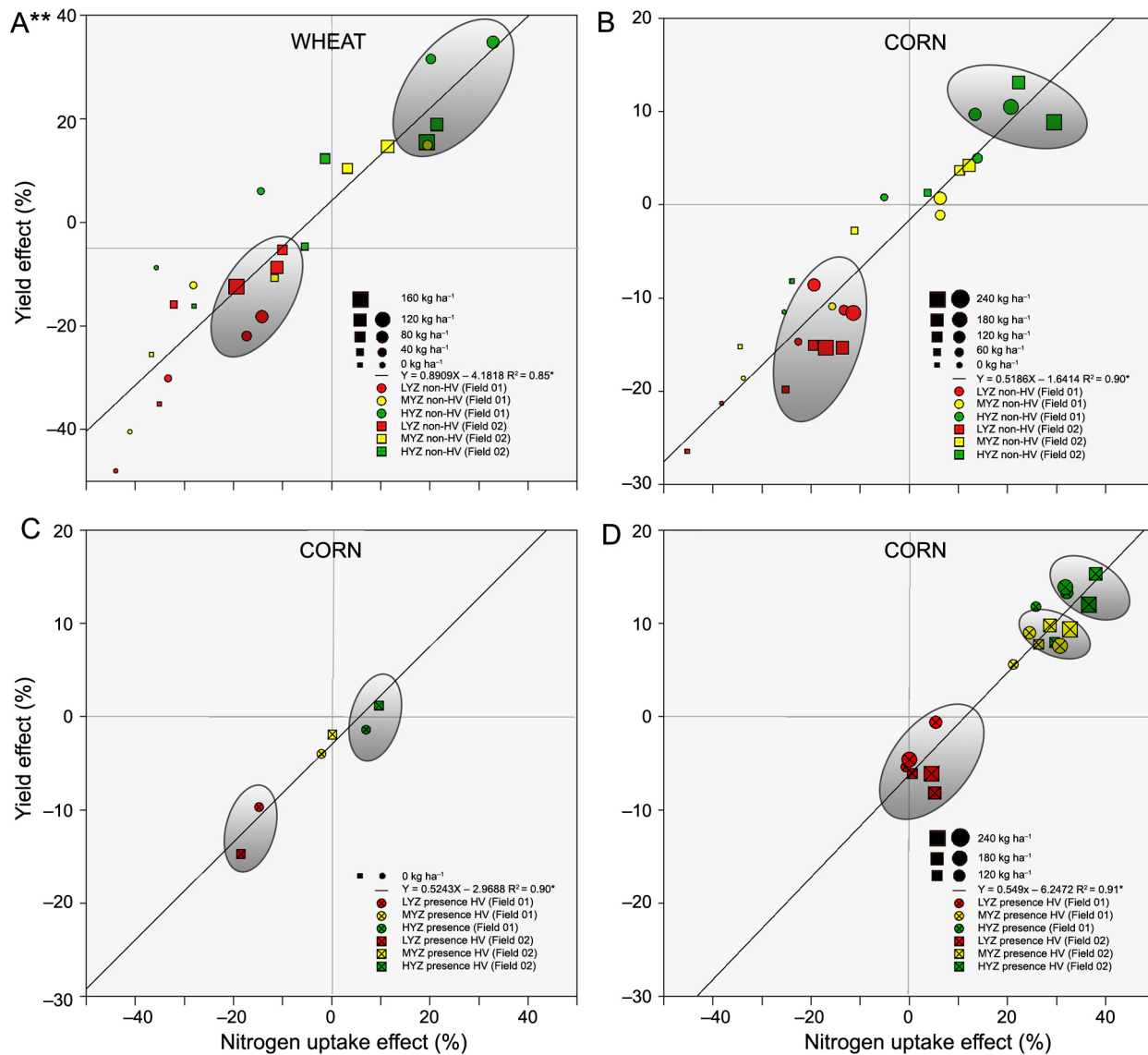


Figure 4 – Crop yield gap associated to N uptake. A) Wheat yield gap - incremented N fertilizer rates, non-hairy vetch; B) Corn yield gap - incremented N fertilizer rates, non-hairy vetch; C) Corn yield gap - without N fertilizer rates, with hairy vetch and D) Corn yield gap - non-limited N fertilizer rates, with hairy vetch; in Field 1 and Field 2. LYZ = low yield zone, MYZ = medium yield zone, HYZ = high yield zone and HV = hairy vetch. *Correlation coefficient (R^2) is significant ($p < 0.05$). **Wheat data adapted from Schwalbert et al. (2018a).

Our results show that LYZ and MYZ require a combination of organic and mineral strategies to mitigate grain yield gap in relation to the reference. While for HYZ, mineral N fertilization in single use or combined with HV was efficient to maximize yield. Given the ecosystem services, environmental impact and sustainability, mineral N fertilization should be replaced partially by legume cover crop without penalizing grain yield. In the same sense, Perveen et al. (2019) reported that high mineral N fertilizer input can decrease soil microbial biomass not only in shallow layers but also in the subsoil.

Conclusion

In both fields of management zones, HV increased corn N uptake and grain yield. The higher N contribution of HV to corn N uptake and grain yield was found in the absence or under low N fertilizer rate.

In the low yield zone, in both fields, corn and wheat had lower N uptake when the N fertilizer rate exceeded 120 kg ha⁻¹ and 80 kg ha⁻¹, respectively. Therefore, the strategy to apply high mineral N fertilizer rates to increase crop yields in the low yield zone can result in low economic return and high environmental impact.

HV as cover crop mitigated partially the yield gap between the management zones, ensuring that the middle yield zone had no yield difference to high yield zone.

The combined use of HV and mineral N fertilization rate adjusted according to N legume credit and management zones was an effective strategy to boost yield, benefiting soil health and providing environmental protection.

Authors' Contributions

Conceptualization: Pes, L.Z.; Amado, T.J.C.; Gebert, F.H. **Data acquisition:** Gebert, F.H.; Pott, L.P.; Schwalbert, R.A. **Data analysis:** Gebert, F.H.; Pott, L.P.; Schwalbert, R.A. **Design of methodology:** Amado, T.J.C.; Gebert, F.H.; Pott, L.P.; Schwalbert, R.A. **Software development:** Gebert, F.H. **Writing and editing:** Pes, L.Z.; Amado, T.J.C.; Gebert, F.H.; Pott, L.P.; Schwalbert, R.A.

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