Science of the Total Environment 759 (2021) 144313

Contents lists available at ScienceDirect

Science of the Total Environment

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

Effect of hairy vetch cover crop on maize nitrogen supply and productivity at varying yield environments in Southern Brazil

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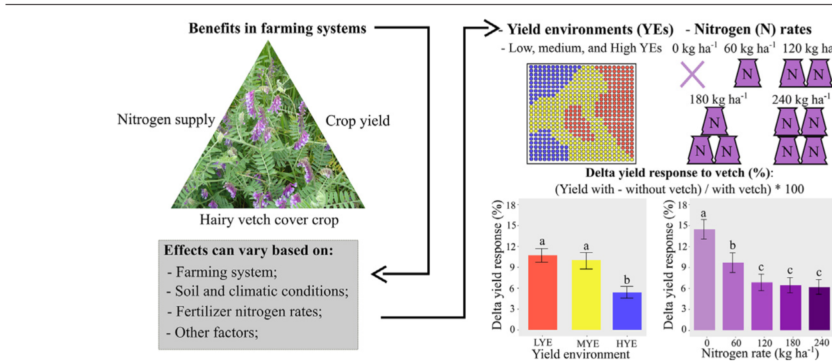
HIGHLIGHTS

- Vetch effects were largest for low N rates and low-to-medium yield environments.
- Vetch combining with N fertilizer was critical for satisfying maize N supply and improving yields.
- N nutrition index at maize flowering was an efficient index for reflecting the vetch effect.
- The N fertilizer replacement value reflects the largest contribution of vetch to maize N nutrition in low yield environment.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 8 August 2020
Received in revised form 13 November 2020
Accepted 26 November 2020
Available online 9 December 2020

Editor: Ouyang Wei

Keywords:
Vicia villosa Roth
Yield environment (YE)
Nitrogen fertilizer rate
Nitrogen uptake
Nitrogen nutrition index (NNI)
Nitrogen fertilizer replacement value (NFRV)

ABSTRACT

Cover crops play a critical role on conservation and sustainable agriculture due to their well-documented benefits on both soil and crop productivity. Inclusion of legumes (e.g., hairy vetch, *Vicia villosa* Roth) in the farming system can reduce the nitrogen (N) fertilizer needs for cereals such as maize (*Zea mays* L.) crop while maintaining or increasing its productivity. The aims of this research study were to quantify the effect of hairy vetch as a cover crop on: i) successor maize yield under varying yield environments (YEs) and fertilizer N rates, and ii) maize N status [N uptake, N nutritional index (NNI), and N fertilizer replacement value (NFRV)] at flowering time. Two field studies were carried out in Southern Brazil under varying YEs. The factors investigated were: YE (low, medium, and high), hairy vetch cover crop (with and without), and fertilizer N rate (0, 60, 120, 180, and 240 kg N ha^{-1}). Under the combination of low YE and low fertilizer N rates (0–60 kg ha^{-1}) with previous vetch, maize displayed the largest yield response and an improvement in its N status. The NNI determined at maize flowering was an efficient index of the vetch effect, increasing delta maize yield response (yield with- minus without-vetch) as the NNI reduced, with more than 10% delta yield response with NNI below 0.85. The NFRV of the hairy vetch represents potential N savings of 151 kg N ha^{-1} for the LYE, 95 kg N ha^{-1} for the MYE and from 59 to 45 kg N ha^{-1} for the HYE depending on the tested fertilizer N rate. The N coming from the legume cover crop in addition to the N fertilization was critical for supplying N to maize and boosting productivity across all YEs.

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https://doi.org/10.1016/j.scitotenv.2020.144313
0048-9697/

1. Introduction

No-tillage system in agriculture emerged as a basis for conservation and sustainable agriculture in tropics (Lal et al., 2007), gradually improving soil quality (Mielniczuk et al., 2003). Conservation agriculture, when implemented (permanent soil cover, crop rotation and minimum mechanical soil disturbance), contributes to soil protection, increases productivity and results in a more efficient use of natural resources (Hobbs et al., 2008; Amado et al., 2020).

Globally, cover crops (especially legumes) play a key role in conservation agriculture, improving soil organic carbon (Bayer et al., 2009; Veloso et al., 2018), providing biomass inputs, cycling and fixing nitrogen (N), and in overall promoting a positive impact on the crops following the rotation (Amado et al., 2006; Acosta et al., 2011; Calonego et al., 2017; Pott et al., 2019). A recent meta-analysis compiling 60 studies reported an overall increase in soil microbial abundance, activity, and diversity compared to the scenario with bare fallow (Kim et al., 2020). Furthermore, a different meta-analysis focused on global cropland documented increases in soil organic carbon due to cover crops (Jian et al., 2020). Likewise, a meta-analysis (data from US and Canada) focusing on the effect of legumes on maize crop (*Zea mays* L.) demonstrated the effect of the previous crop on yields even under low fertilizer N rates (Marcillo and Miguez, 2017). In addition, adoption of cover crops is an alternative to grow during the fallow period (Pinto et al., 2017), using a small proportion of the available resources without competing with the main cash crop (Caviglia, 2004) and promoting ecosystems services. Lastly, a recent meta-analysis provided evidence that cover crops offer a service for the mitigation of nitrate pollution, but with trade-off of reducing drainage (Meyer et al., 2019).

Previous studies around the world have already shown the effect of including a legume such as hairy vetch (*Vicia villosa* Roth) as a winter cover crop following of a cereal demonstrating the importance on the N dynamics (Coombs et al., 2017) and assessing the N fertilizer replacement value (NFRV) of the cover crop (referred to "cover crop N credits"). The NFRV represents the total quantity of mineral fertilizer N saved when comparing the same crop in rotation with a cover crop as a predecessor, while attaining equal yield (Ketterings et al., 2015). Other potential benefits to be listed for N-fixing legume as cover crop are related to the enhanced of maize N uptake (Seo et al., 2006; Gabriel and Quemada, 2011), farm-economic profitability (Preissel et al., 2015), and ultimately, boosting maize yields (Miguez and Bollero, 2005; Coombs et al., 2017; Wittwer et al., 2017). Potential offsets to the benefits of cover crops on the following crop could be observed for water use in water limited environments (Kramberger et al., 2009).

Cover crop benefits to next crops in the rotation vary based on its biomass production (Amado et al., 2002; Sievers and Cook, 2018; Thapa et al., 2018), farming systems - crop type/rotation (Parr et al., 2011; Wittwer et al., 2017; Thapa et al., 2018), soil and climatic conditions (Gabriel and Quemada, 2011; Preissel et al., 2015), and fertilizer N rates (Preissel et al., 2015; Coombs et al., 2017).

The introduction of N-fixing legumes such as hairy vetch will benefit the system by providing additional N, with biological N fixation (BNF) ranging from 72 to 89% of the plant N demand (Acosta et al., 2011; Wittwer et al., 2017). Thus, the N surplus can greatly benefit the next crop in the rotation, more in the case of a high-yielding and N demanding cereal crop such as maize (Tonitto et al., 2006; Gabriel and Quemada, 2011; Wittwer et al., 2017). Nonetheless, the complex N cycling and synchrony between soil N supply and plant N demand can affect not only the N supply for next crop (Crews and Peoples, 2005), but also the potential response to the fertilization practice (Blevins et al., 1990; Mahama et al., 2016).

Management responses under varying crop and soil productivity levels has not been well addressed in the scientific literature, less if considering the effect of cover crops. Delimitation of yield environments (YEs), zones within a field with similar productivity, can promote useful interventions successfully impacting crop productivity (Breunig et al., 2020). Implementation of management regarding well-defined YEs such as tillage (Edreira et al., 2017), plant density (Corassa et al., 2018; Schwalbert et al., 2018; Carciochi et al., 2019), fertilization rate (Schwalbert et al., 2019), and mitigation of soil compaction (Pott et al., 2019) have demonstrated clear benefits for land management.

Thus, the aims of this research study were to quantify the effect of hairy vetch as a cover crop on: i) successor maize yield under varying YEs and fertilizer N rates, and ii) maize N status [N uptake, N nutritional index (NNI), and N fertilizer replacement value (NFRV)] at flowering time.

2. Material and methods

2.1. Field experimental sites

Two experiments were carried out in Southern Brazil, in the city of Carazinho, Rio Grande do Sul, Brazil. The first study (Site 1, deployed in a 134 ha farm field, 2014/15 growing season) located in 28.320° S, 52.705° W, with an altitude of 535 m, and the second one (Site 2, deployed in a 54 ha farm field, 2015/16 growing season) located in 28.324° S, 52.731° W, with an altitude of 550 m (Fig. 1).

The experimental sites consisted of annual crops (maize, soybean [*Glycine max* (L.)], and cover crops such as black oat [*Avena strigosa* (Schreb.)] and hairy vetch managed under long-term no-till system (more than 10 years), and with the last seven years utilizing precision agriculture practices based on data-driven management using yield monitor equipment, soil apparent electric conductivity (ECa), periodic soil sampling and fertilizer variable-rate inputs.

The soils of both sites were classified as Typic Hapludox according to U.S. Soil Taxonomy (Soil Survey Staff, 2014). According to Alvares et al. (2013) the climate of the sites is a humid subtropical Cfa, with an annual average temperature of 18.4 °C and annual precipitation of approximately 1730 mm well distributed through the months.

2.2. Yield environments delineation and soil properties

Yield environments were delineated by aggregating previous maize yield data (past yield monitor harvest data from two maize growing seasons), ECa, and terrain elevation data for both sites (Table 1). The previous maize yield data for site 1 were evaluated in 2011/12 and 2013/14 seasons, while for site 2 were in 2013/14 and 2014/15 seasons. The maize yield data was collected using an infrared harvesting sensor (Stara APS®, Não-Me-Toque, Brazil), installed in a New Holland TC5090 combine (CNH, Curitiba, Brazil). The ECa data was collected with Veris EC 3150® (Veris Technologies; Stara, Não-Me-Toque, Brazil). The Veris EC uses rolling coulter electrodes to directly sense soil electric conductivity (Sudduth et al., 2005). Field measurements were collected in a series of parallel transects spaced at 15–20 m intervals as recommended by Farahani and Flynn (2007) in depths of 0 up to 0.30 m and 0 up to 0.90 m on April 3, 2014, when soil moisture was close to the point of friability for both sites. Further, the terrain elevation data were obtained from GPS Novatel® with Ominstar HP correction equipped in the combine collected simultaneously with the previous maize yield.

The geospatial data of previous maize yield, ECa and elevation were utilized to create classes and to delineate three yield environments: low (LYE), medium (MYE), and high (HYE) using the fuzzy k-means method. Fuzzy k-means is a clustering technique using an iterative procedure that starts with an initial random allocation of the objects to be classified to k clusters. This technique is extensively applied to delineation of uniform environments within fields (Fridgen et al., 2004; Tagarakis et al., 2013; Gili et al., 2017).

Soil samples were collected at the 0-to-0.20 m soil depth with four replications to analyze soil properties of the delineated YEs. The properties were: pH (analyzed in H_2O), clay content (analyzed with

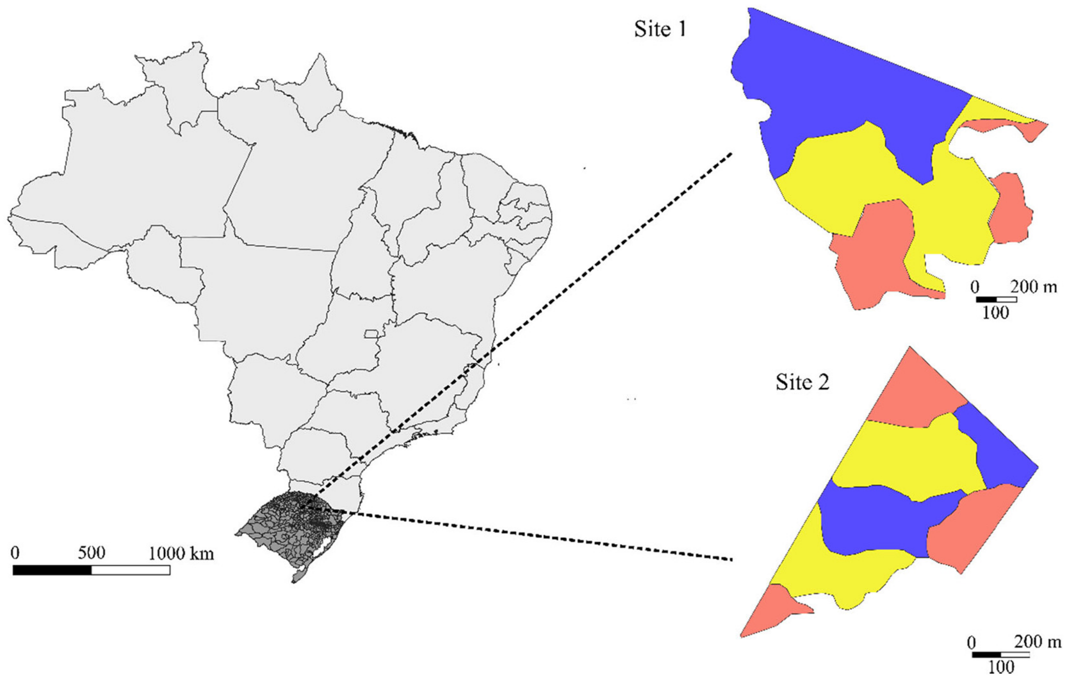

Fig. 1. Experimental locations (Sites 1 and 2) in Rio Grande do Sul State, Brazil. The area of each site was divided in three yield environments (YEs), low (LYE) (red color), medium (MYE) (yellow color), and high yield environment (HYE) (blue color).

densimeter after dispersion in NaOH solution), soil organic matter (SOM) (analyzed with sulfochromic solution with external heat and spectrophotometric determination of Cr^{+3}), total N content [Kjeldhal digestion (Page, 1982)], inorganic N (NH_4^+ -N + NO_3^- —N, KCl extraction, methodology from Bremner and Keeney, 1965), available P and K^+ (extracted by Mehlich-1) contents, exchangeable Ca^{2+}, Mg^{2+} (extracted by 1 mol L^{-1} KCl solution) (Table 2). All the procedures are described in Tedesco et al. (1995), the most accepted methodology for soil analyses in Rio Grande do Sul, Brazil.

2.3. Experimental design, treatments, and data collection

The study was conducted in a randomized complete block design, with a 3 × 2 × 5 factorial arrangement, with three replications. The factors were: yield environment (LYE, MYE, and HYE), hairy vetch cover crop (with and without), and fertilizer N rate (0, 60, 120, 180, and 240 kg N ha^{-1}). Each experimental unit was 8 by 4 m, totaling 2880 m^2 of experimental area for each site.

The hairy vetch cover crop was sown by a distributor equipped with double disk centrifuge model Hércules 5.0 (STARA, Não-Me-Toque, Brazil) at mid-April for site 1 (April 15) and early April for site 2 (April 3), using 20 kg ha^{-1} of SS Esmeralda® genotype. Fertilizers were not added during the hairy vetch phase. The hairy vetch was killed after flowering (roughly 2 weeks after) stage, by applying a non-selective glyphosate herbicide at a rate of 2.0 kg ha^{-1} followed by a knife roller-crimper operation, executed ten days before maize sowing.

The plots with hairy vetch provided different dry biomass and N content for the treatments (Table 3). The hairy vetch biomass production was evaluated (four replicates) at termination time by collecting above-ground crop biomass within a 1 by 1 m square. The cover crop residues were dried in a forced air oven at 60 °C for 48 h and dry biomass was determined. The N concentration of dry tissues was obtained by grounding and passing through a 1-mm sieve to determine N concentration (%N) using micro Kjeldahl method (H_2O_2 and H_2SO_4 digestion), according to Tedesco et al. (1995).

All maize plots were sown utilizing a Pioneer (Johnston, IA, US) 30F53YH hybrid with a target plant density of 64,000 plants ha^{-1} for mid-September (September 15) for site 1, and early September (September 7) for site 2. Basal fertilization was accomplished by applying 280 kg ha^{-1} of 10–25-25 (N-P_2O_5-K_2O), representing 28, 31, and 58 kg ha^{-1} for N, P, and K, respectively. The N rates were applied manually on top-dress at maize V4 growth stage (Hanway and Ritchie,

Table 1
Mean comparison for the variables used in the yield environment (YE) delineation: maize yield, terrain elevation and apparent electric conductivity.

Variables	Site 1			Site 2		
	LYE	MYE	HYE	LYE	MYE	HYE
Grain yield (kg ha^{-1})*	5990 c	6930 b	8800 a	8490 c	10,370 b	11,320 a
Terrain elevation (m)	514 b	533 a	538 a	555 b	566 a	562 a
ECa 0–0.3 m (mS m^{-1})	5.8 b	7.7 a	8.0 a	5.1 c	6.5 b	8.0 a
ECa 0–0.9 m (mS m^{-1})	68 c	90 b	106 a	60 c	73 b	91 a

* Average over two growing seasons for the maize yield maps in each site. For each site and variable, different letters indicate significant differences between YEs (Tukey's test, P < 0.01). ECa: apparent electric conductivity. LYE: low YE. MYE: medium YE. HYE: high YE.

Table 2
Soil properties (0–0.20 m soil depth) from each site and yield environment (YE).

Properties	Site 1			Site 2		
	LYE	MYE	HYE	LYE	MYE	HYE
pH (1:1)	5.4 a	5.4 a	5.3 a	4.6 b	4.9 b	5.4 a
SOM (g kg^{-1})	24 b	31 a	32 a	23 b	29 a	32 a
Total N (g kg^{-1})	1.3 b	1.4 a	1.4 a	1.1 b	1.3 a	1.3 a
Inorganic N (mg kg^{-1})	25 b	27 a	28 a	22 b	24 a	24 a
Clay (g kg^{-1})	500 b	680 a	640 a	420 b	590 a	600 a
P (mg kg^{-1})	4.2 c	12.4 b	13.8 a	12.2 c	15.3 b	16.2 a
K^+ (mg kg^{-1})	118 c	156 b	189 a	115 c	134 b	142 a
Ca^{2+} ($cmol_c$ dm^3)	6.3 a	6.5 a	6.4 a	3.5 c	5.1 b	6.2 a
Mg^{2+} ($cmol_c$ dm^3)	2.9 a	2.8 a	2.5 a	1.2 c	1.7 b	2.3 a

For each site and variable, different letters indicate significant differences between YEs (Tukey's test, P < 0.01). SOM: soil organic matter. LYE: low YE. MYE: medium YE. HYE: high YE.

Table 3
Hairy vetch biomass and N content for each site and yield environment (YE).

Variable	Site 1			Site 2		
	LYE	MYE	HYE	LYE	MYE	HYE
Dry biomass (kg ha^{-1})	5332 c	5589 b	5834 a	4234 c	4563 b	4724 a
N content (kg ha^{-1})	205 b	215 a	212 a	188 b	199 a	199 a

For each site and variable, different letters indicate significant differences between YEs (Tukey's test, $P < 0.01$). LYE: low YE, MYE: medium YE, HYE: high YE.

1984), using urea (45% N) as N source. Basal fertilization and N rate levels were defined according to Commission Soil Chemistry and Fertility of Rio Grande do Sul and Santa Catarina states (CQFS-RS/SC, 2016).

For each plot, six plants were harvested at silking stage (R1 growth stage; Hanway and Ritchie, 1984), dried at 60 °C for 48 h to determine the corresponding dry biomass. After dry weight was evaluated, samples were ground and passed through a 1-mm sieve to determine N concentration (%N) using micro Kjeldahl method (H_2O_2 and H_2SO_4 digestion) according to Tedesco et al. (1995). Total N uptake was determined as the product of biomass and its respective %N.

The N nutrition index (NNI) was computed as the ratio between %N and the critical N concentration ($\%N_c$) (Eq. (1)). The $\%N_c$ was calculated using plant biomass based $\%N_c$ curves of maize (Lemaire et al., 2008) (Eq. (2)).

$$NNI = \frac{\%N}{\%N_c} \quad (1)$$

$$\%N_c = a_c(W)^{-b} \quad (2)$$

where $a_c = 3.4$; W = dry biomass (Mg ha^{-1}); $b = 0.37$.

Maize grain yield was obtained by harvesting 18 ears from consecutive and evenly spaced plants from each plot, stored and measured for kernels per ear, kernel weight and grain yield. The grain yield was calculated multiplying kernels per ear by kernel weight by plant density to obtain a per-unit-area yield.

The difference in maize N uptake with and without vetch was calculated for all combinations of fertilizer N rates and YEs. The NFRV was calculated by the "difference" method (Shrader et al., 1966; Lory et al., 1995). In the difference method, the NFRV is calculated by the N application required for corn to reach a yield equal to that of corn after the cover crop evaluating in different N rates (Ketterings et al., 2015). The NFRV assessment has been executed for each YE and N rate combination.

Relative grain yields (individual data points) were calculated as the grain yield of each plot divided by the yield achieved by the highest N rate (240 kg ha^{-1}) with vetch for each YE within the same block. The delta maize yield response to vetch (%) was calculated as the difference between maize yield with and without vetch, divided by the yield with vetch multiplied by 100 (Eq. (3)).

$$\text{Yield response to vetch } (\%) = 100 * \frac{\text{yield}_{\text{with vetch}} - \text{yield}_{\text{without vetch}}}{\text{yield}_{\text{with vetch}}} \quad (3)$$

2.4. Statistics

The factors YE, vetch, and N rate and their interactions were considered fixed effects. There were no statistical differences in the variance between sites evaluated using the Levene's test, thus, the homogeneity of variance assumption between sites was met. For the analysis, blocks were nested within sites and they were considered as random. The data were subjected to analysis of variance (three-way mixed ANOVA type III, F test, $P < 0.01$) and the means of the treatments were compared by Tukey's test ($P < 0.01$). Linear-plateau regression was performed to analyze the grain yield. Delta yield response to vetch was assessed to analyze the response of the vetch in one-way ANOVA for each factor (YEs, Vetch, and N rates). Linear and bilinear regression models were used to analyze the relationships between relative yield and NNI. Linear regressions were performed to analyze the delta yield response to vetch associated to NNI, in addition, the relationship between the additional N uptake of maize due cover crops relative to maize N rates. All statistical analyses were carried out using the R software (R Core Team, 2019).

3. Results

3.1. Maize yield (productivity)

The three factors (YE, vetch cover crop, and N fertilizer rate) impacted maize yield, with significant differences (Supplementary Table 1). As expected, the HYE resulted in the highest yield, more when combined with the presence of vetch as predecessor cover crop, while the LYE without vetch presented the lowest maize yield. Nevertheless, with the presence of vetch, maize yields were greater than without vetch across all YEs (Fig. 2A).

Fertilizer N rates increased maize yields as YE improved. Maize yield increased as the fertilizer N rate rise until 180 kg N ha^{-1}, with no significant increment in maize yield when N fertilizer rate was greater than 180 kg N ha^{-1}, for all the YEs. Nonetheless, YEs presented different attainable yields from low to high YEs in order: ~11,550, ~13,350 and ~14,080 kg ha^{-1}, respectively (Fig. 2B).

Maize yields increased with N fertilization until the N rate of 180 kg N ha^{-1}, regardless the effect of cover crop. However the largest yield gap (1300 kg ha^{-1}) due to vetch occurred when the N rates were below 60 kg N ha^{-1}. The changes in yield due to increasing N fertilization rates were more evident in those treatments when vetch was not included as previous crop (Fig. 2C).

3.2. Factors associated with vetch in response to the maize yield

Across all tested factors, maize yield increased by 8.3% with vetch presence relative to the control, without vetch (Fig. 3A). For the YEs, LYE presented the greater delta yield response, not differing from MYE, while the HYE resulted in the lower delta yield response (estimated as a delta yield response (%) to vetch) (Fig. 3B). For the fertilizer N factor, low N rates (0 and 60 kg ha^{-1}) presented the greater maize yield response (14.5 and 9.7%, respectively) with vetch presence, while yield responses under higher N rates were 6.9, 6.2, and 5.9% for the 120, 180, and 240 kg ha^{-1}, respectively (Fig. 3C).

3.3. Vetch benefits on N status and yield response for maize

Relative maize yield was associated to NNI in a linear-plateau relationship for each YE (Fig. 4A). For the LYE, the relative yield rises as the NNI increased until NNI threshold close to 1, to be more precise 1.1 and then plateaued, while for the MYE and HYE the plateau level was attained at 1.35 and 1.40, respectively. The relative yield responded linearly with low N rates (0–60 kg ha^{-1}), but further increases in N fertilization (180–240 kg ha^{-1}) were not reflected in yields but in high NNI levels (Fig. 4A).

The differential relative maize yield response to vetch (relative to without vetch) was greater (12–16%) in the LYE with low N rates (0–60 kg ha^{-1}), with NNI without vetch (reflecting the lack of N addition from this previous crop) levels below 0.85 units. In overall, the delta yield response to vetch decreased linearly as NNI in plots without vetch increased, with the majority of the observations falling below the 1.0 NNI (all N rates from LYE, and 0 kg ha^{-1} N rate from MYE and HYE) portrayed delta yield response greater than 8%, while high N rates from MYE and HYE presented values well above 1.0, luxury N uptake scenario (Fig. 4B).

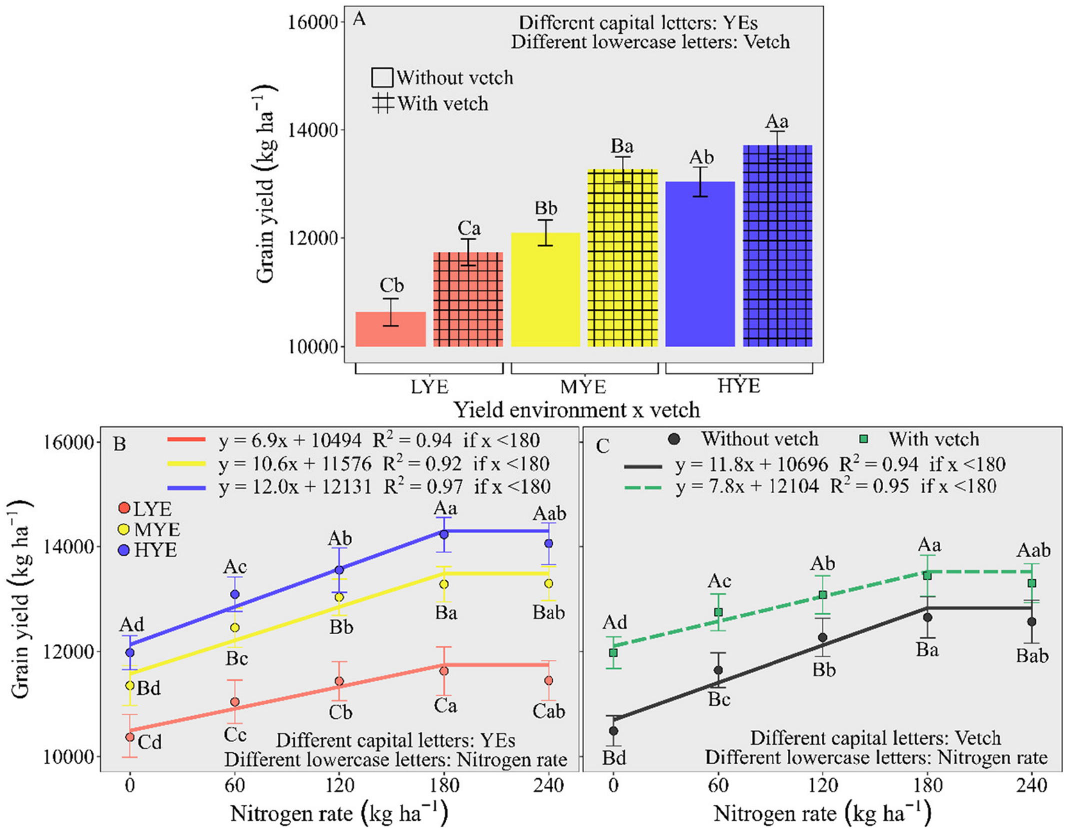

Fig. 2. (A) Maize yield relative to yield environment (YE) by with and without hairy vetch, (B) YEs by fertilizer nitrogen (N) rate, and (C) vetch by fertilizer N rate (C) across evaluated sites. Different letters indicate significant differences between levels of the factors (Tukey's test, P < 0.01). Vertical error bars indicate the standard error (SE).

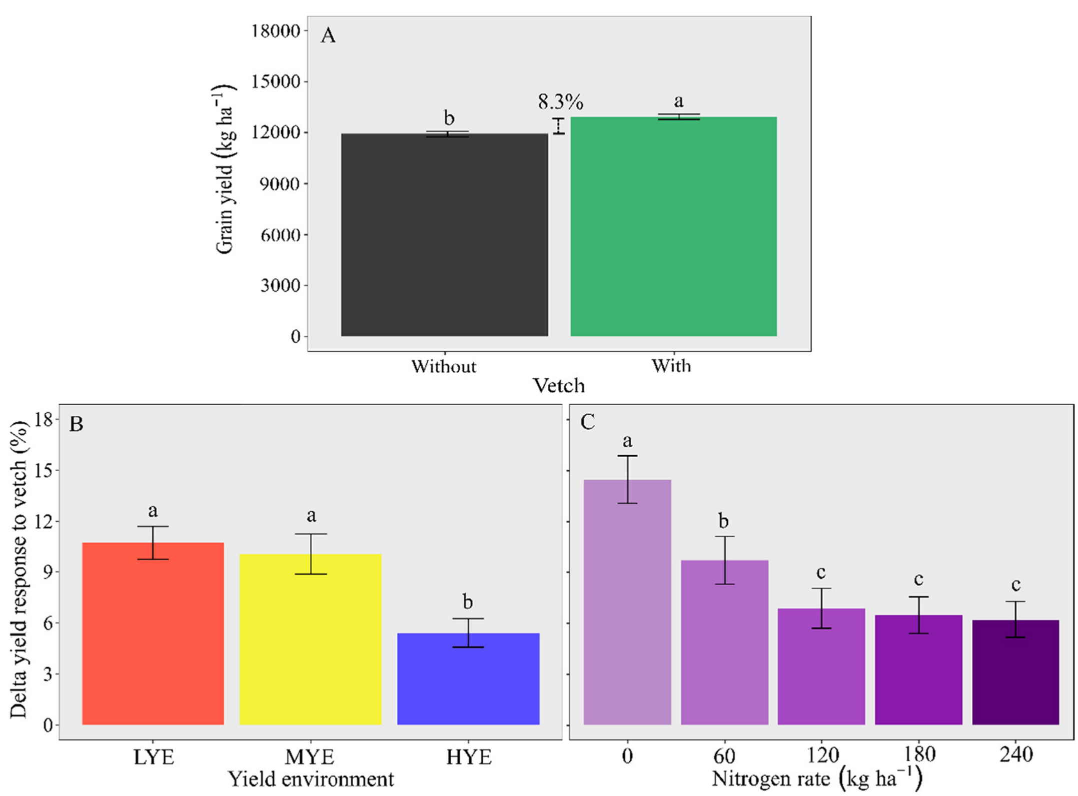

Fig. 3. (A) Overall effect of hairy vetch in maize grain yield, (B) hairy vetch effect under yield environments, and (C) hairy vetch effect under fertilizer nitrogen (N) rates all obtained across evaluated sites. Delta yield responses to vetch (%) was calculated as the difference between with minus without vetch for maize yields, divided by the yield with vetch × 100. Different letters indicate significant differences between levels of the factors (Tukey's test, P < 0.01). Vertical error bars indicate the standard error (SE).

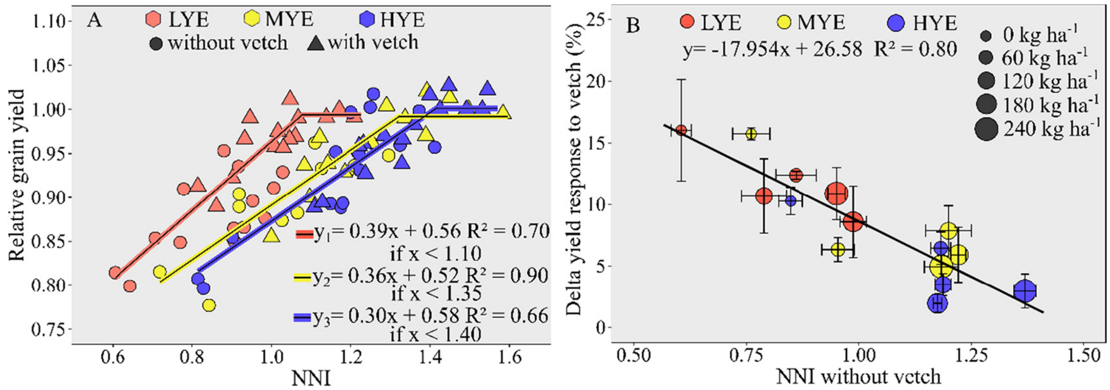

Fig. 4. (A) Relationship between relative maize yield and nitrogen (N) nutrition index (NNI). The solid line represents a bilinear regression of the data. Relative grain yields (individual data points) were calculated as the grain yield of each plot divided by the yield achieved by the highest N rate (240 kg ha^{-1}) with vetch for each yield environment (YE) within the same block. (B) Relationship between delta yield response to vetch (%) and NNI without vetch. Delta yield response to vetch (%) was calculated as the difference between with vetch and without vetch for maize yields, divided by the yield with vetch × 100. The YEs are presented in different colors: low YE (LYE), medium YE (MYE), and high YE (HYE). Vetch is presented in different shapes. Fertilizer N rates are presented in different symbol sizes. Vertical and horizontal error bars indicate the standard error (SE).

The effect of vetch as a predecessor crop increased maize N uptake roughly by 41 kg N ha^{-1} across all fertilizer N rates. However, the delta N uptake in maize due the vetch presence was greater under low fertilizer N rates (well above 40 kg N ha^{-1} when the N fertilizer rate was below 60 kg N ha^{-1}), but not differing across all the evaluated YEs (Fig. 5A).

The NFRV for the LYE without vetch attained only a similar yield relative to the treatment with vetch without N fertilization but needed 151 kg N ha^{-1} (Fig. 5B). Similar for the MYE, same scenario was reached without vetch when 95 kg N ha^{-1} was applied. However, for the HYE, NFRV equaled to 59, 59 and 45 kg N ha^{-1} for a N fertilization level without vetch of 0, 60, and 120 kg ha^{-1} N rates, respectively (Fig. 5B).

4. Discussion

This study highlights the benefits of using a legume as a cover crop for reducing maize dependency on N fertilization and boosting grain yield, while acknowledging the differential effects of this practice under diverse productivity zones within the field. To the extent of our knowledge, this is one of the first studies identifying the effect of this practice considering the intrinsic variation naturally occurring within farmer fields with the main goal of driving adequate land management changes not only to maximize productivity but improve the N fertilization footprint from an environmental standpoint.

Previous studies emphasized the effect of hairy vetch as an efficient predecessor crop for: i) weed suppression (Hayden et al., 2012; Wittwer et al., 2017), ii) green manure increasing fungi biomass and community composition (Kataoka et al., 2017), iii) increasing earthworms (Ashworth et al., 2017), iv) increasing soil nutrient supply (Liu et al., 2018), v) reducing erosion, vi) improving the overall soil health (Chatterjee and Clay, 2017; Amado et al., 2020), and vii) mitigating climate change by integrating fertilization (Guardia et al., 2019). The overall responses of cover crops in the subsequent crop in the rotation may vary with tillage systems (Miguez and Bollero, 2005), climate (Enrico et al., 2020), weed infestation (Hayden et al., 2012; Yeganehpoor et al., 2015) and soil properties (Balbinot et al., 2011; Choi et al., 2018; García-González et al., 2018; Majumder et al., 2018; Silva et al., 2019).

The quality of environmental sources such as water, soil and crops vary temporally and also spatially by their bio-physical and-chemical properties, in this way, management practices considering the variability within agricultural systems are needed to improve the sustainable land management (Key et al., 2016; Hou et al., 2020). In our study, the use of vetch as cover crop led to a differential impact in maize grain yield regarding the YEs and N rates applied to this crop. The largest yield response was documented under environments with low productivity and with limited or none mineral N fertilizer input. These results are in agreement with previous studies portraying benefits of legume cover crops in maize yield,

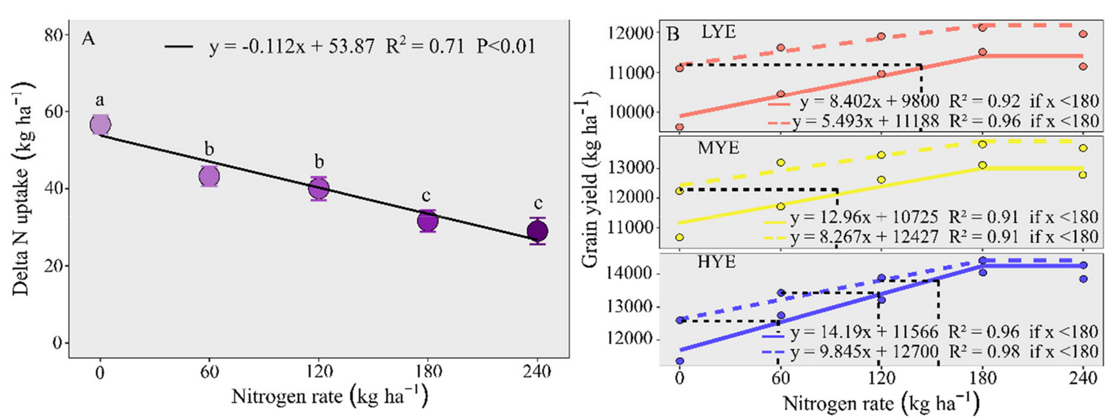

Fig. 5. (A) Delta maize nitrogen (N) uptake (N uptake with minus without vetch) by fertilizer N rates. Different letters indicate significant differences between N rates (Tukey's test, $P < 0.01$). Vertical error bars indicate the standard error (SE). (B) Maize yield with and without vetch in relationship to fertilizer N rate levels under varying yield environments (YEs). Solid colorful lines represent yield regressions from without vetch, while dashed lines represent regressions from with vetch for low YE (LYE) (red color), medium YE (MYE) (yellow color), and high yield environment (HYE) (blue color). Black dashed lines represent the N fertilizer replacement value (NFRV) when it was achieved in the YE and N rate.

consistently increasing maize yield with reduced fertilizer N rates applied to this crop (Miguez and Bollero, 2005; Marcillo and Miguez, 2017; Tonitto et al., 2006). The latter highlights the potential of legume cover crops (e.g., hairy vetch) as one of the main N sources for maize crop when the systems are less input intensive (organic production, Yang et al., 2019) and to maintain yields when tillage is reduced (e.g. conservation agriculture; Wittwer et al., 2017).

Plant development and crop productivity are determined by the interactions between the plant subsystem and the specific field environment, such as genotypes, soil conditions and climate arrangement (Angers and Caron, 1998; Nicolodi and Gianello, 2015; Pott et al., 2019). Following this rationale, hairy vetch provided an additional benefit to the system by adding N via the BNF process (Preissel et al., 2015; Enrico et al., 2020). Positive effects on maize productivity and plant N status with vetch as cover crop are in agreement with those reported by Gabriel and Quemada (2011) and Spargo et al. (2016). However, the overall N contribution from vetch depends of several factors such as the legume-rhizobium interaction (Laguerre et al., 2007), legume biomass production (Collino et al., 2015; Thapa et al., 2018), N accumulation (Thapa et al., 2018), soil available N (Ketterings et al., 2015; Coombs et al., 2017).

The biomass and N content of hairy vetch cover crop in our research presented values within the range of previous studies reported in the literature (Thapa et al., 2018). However, the available N content of the cover crop for the subsequent maize is dependent of the synchrony between cover crop residue decomposition rate with crop N demand (Crews and Peoples, 2005; Sievers and Cook, 2018).

In-season maize plant N status, reflected by the NNI, was an efficient indicator for the potential effect of the N contribution from the vetch crop, with values of NNI at or below 1 showing more yield response, indicating a scenario of N deficiency (Lemaire et al., 2008). Spargo et al. (2016) demonstrated an increase in maize N uptake with the addition of hairy vetch as cover crop. For maize, the literature highlights that values of NNI at flowering below 1 will indicate moderate levels of N stress (Mueller and Vyn, 2018; Fernandez et al., 2020). At field level, cover crops can be grown to reduce the yield gap between current and attainable yields (van Ittersum et al., 2013; Bunselmeyer and Lauer, 2015) considering different YEs with different yield-limiting factors (Pott et al., 2019). Still we acknowledge that the NNI at flowering provides only a 'snapshot' of the effect of the cover crop on the N nutrition of the following crop, and further studies should focus on investigating the residue and soil mineral N dynamics in more detail.

The termination of hairy vetch at 10 days before maize sowing resulted in an increase of N maize uptake at R1 stage by roughly 41 kg ha^{-1} related to situation without cover crop, with this additional N content representing close to 20% of the N content from hairy vetch at termination time. The N recovery of hairy vetch by maize has been reported to vary depending on the biomass input, mineral N and decomposition rates, and maize growth (Acosta et al., 2011), with roughly 12 to 15% N recovery with ^{15}N (Seo et al., 2006; Acosta et al., 2011). In our study, the NFRV ranged from 45 to 151 kg ha^{-1}, highlighting that just the LYE, MYE with 0 N fertilizer and HYE with 0, 60 and 120 kg ha^{-1} reflected values of N fertilization required to obtain a yield equal to that of maize after hairy vetch. Likewise to the NFRV reported in the current study, Ketterings et al. (2015) in a review of cover crops for N management in maize farming systems reported NFRV ranging from 17 to 149 kg ha^{-1}.

The NFRV presented in our study reflected the benefits of hairy vetch cover crop, not only by the N supply, but also the entire cover crop effect such as improving the overall soil health (Chatterjee and Clay, 2017; Amado et al., 2020). The NFRV depends on the weather (Bruulsema and Christie, 1987; Utomo et al., 1990), soil organic matter levels, soil physical conditions, water relations (Frye et al., 1985; Utomo et al., 1990), and the maturity stage of the cover crops at the time of termination (Ketterings et al., 2015). Our findings are in agreement with the additional N application associated with cover crops can promote greater attainable yield than the scenario with mineral N application in maize without the cover crop effect (Decker et al., 1994; Crews and Peoples, 2005; Wittwer et al., 2017).

Although this study focuses on characterizing the effect of vetch on maize primarily from the contribution of N standpoint, a more holistic research should be executed to determine other beneficial effects of cover crop linked to nutrient cycling, weed suppression, and improving biological system under varying productivity levels (YEs). In addition, proper assessment of the contribution of N-fixing process in cover crops for legume-based systems will provide a more comprehensive view on the holistic N cycling and associated effects on soil and impact on the next crop in the rotation.

5. Conclusions

The hairy vetch cover crop increased maize yield across all YEs and N rates. However, under LYE and MYE, the delta maize yield response was highlighted compared to HYE. In addition, with low N rates (<60 kg N ha^{-1}), the N contribution from vetch was reflected in a greater delta maize yield response.

For the in-season maize N status, low NNI levels (LYE and N rates <60 kg N ha^{-1}) at flowering were reflected by a high yield and N response to vetch. The overall maize N uptake increased with the vetch effect even under high fertilizer N rates, but with relative yields plateauing and only NNI increasing, reflecting luxury nutrient status. The LYE plateaued with lower NNI, indicating that another factor (not evaluated in this study) is limiting yields for this environment.

Lastly, NFRV suggested that the N contribution derived from the N-fixing legume cover crop in addition to the N fertilization is critical for boosting maize yields, since the NFRV in LYE and MYE was only reached in 0 kg N ha^{-1} fertilizer N rate, but demanding 151 and 95 kg N ha^{-1}, respectively, to achieve similar yield levels without vetch cover crop. Yet, for the HYE, NFRV of the vetch equaled to 59, 59 and 45 kg N ha^{-1} for a N fertilization level without vetch of 0, 60, and 120 kg ha^{-1}, respectively.

Future research studies should focus on providing a more holistic approach to assess the impact of legume-based cover crops in many aspects of the soil-plant system, including not only nutrient cycling, but additional effects on enhancing weed suppression, improving microbial biomass and diversity, mitigating impact of erosion, improving overall soil health, and reducing the environmental footprint of N fertilization in our less diversified farming systems.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.144313.

CRediT authorship contribution statement

Luan Pierre Pott: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing - original draft. **Telmo Jorge Carneiro Amado:** Conceptualization, Validation, Project administration, Writing - review & editing. **Raí A. Schwalbert:** Methodology, Supervision, Validation, Writing - review & editing. **Fábio H. Gebert:** Conceptualization, Data curation, Writing - review & editing. **Geovane B. Reimche:** Investigation, Methodology, Writing - review & editing. **Luciano Z. Pes:** Writing - review & editing. **Ignacio A. Ciampitti:** Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Supervision, Project administration, Writing - review & editing.

Declaration of competing interest

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

Acknowledgements

The authors thank the farmer (Rogério Pacheco and his staff) for their cooperation with this study. This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior, Brasil (CAPES) Finance Code 001. CNPq scholarship for the second author. Aquarius project for financial support and equipment availability. This is Kansas Agricultural Experiment Station contribution number 21-126-J.

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