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A meta-analysis of hairy vetch as a previous cover crop for maize

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ABSTRACT

Background: The use of hairy vetch (*Vicia villosa* Roth.) as cover crop is increasing worldwide. Hairy vetch can contribute as a nitrogen (N) source with potential to impact subsequent high N demanding cereals such as maize (*Zea mays* L.). Contrasting literature results emphasize the need for a global synthesis analysis to quantify changes in maize yield after hairy vetch.

Objectives: A meta-analysis was conducted to i) quantify maize yield response to hairy vetch as previous crop, ii) explore hairy vetch influence on fertilized and non-N fertilized maize yields, and iii) assess the tillage and environment factors on maize yield response to hairy vetch.

Methods: The global systematic search yielded 23 publications selected by the following criteria, i) hairy vetch dry matter at the end of the season, ii) maize grain yield, and iii) experimental design with (Mz_{hv}) and without ($Mz_{control}$) hairy vetch treatments. Information such as N fertilization for maize, N accumulation in hairy vetch, organic matter, and tillage before maize sowing were recorded. Hairy vetch effects (effect size) were expressed as a ratio (percentage of grain yield variation in $Mz_{hv}/Mz_{control}$).

Results: Under non-N fertilization ($n = 9$), results revealed hairy vetch had mostly a positive effect, ranging from 13 to 45% ($n = 6$). In contrast, N-fertilized maize ($n = 20$) showed a high chance of neutral effects ($n = 12$), moderate probability of positive yield impact (7 to 38%, $n = 6$), and a low likelihood of negative effects (−32 and −17%, $n = 2$). Notably, maize yields improved by 21–25% when the N accumulation in hairy vetch ranged from 95 to 150 kg ha^{-1} and N rate from 0 to 120 kg ha^{-1}. Non-N-fertilized maize exhibited a 14% increase in response in no-till systems and a 31% increase with conventional tillage.

Conclusion: This study summarizes potential benefits of hairy vetch preceding maize. Yet, the heterogeneous outcomes deserve further exploration in terms of environment and management factors.

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1. Introduction

Crop diversification has decreased over time with the focus on obtaining short-term effect of high yields, but with fewer crops per year [1]. More recently [2], reported that increasing landcover diversity is linked to yield increases for major crop yields. In addition to the problem of low crop diversification, the increase in the number of crops per year, herein termed as intensification, should be considered to increase production with limited agricultural land area [3]. Altogether crop diversification and intensification are major challenges to maintain food production for the overgrowing population. From a soil-plant system standpoint, less diversified and intensified farming systems will present challenges linked to i) reduced contribution of plant residues, ii) negative nutrient budgets [4,5], iii) increased dependency to fertilization (mainly nitrogen -N- fertilizers), and iv) the use of inputs to sustain productivity [6]. Among the consequences of these simplified cropping systems, the decrease in soil N availability is especially important as increases the demand of N fertilizers, reaching 112.4 million tons in 2020, being 11% more than in 2010 [7]. Increasing the effective use of N fertilizer, and consequently reducing N losses, mitigating the impact of agriculture on our environment is of primary importance [8]. In this context, conservation agriculture aims to reduce the overall decline in environmental quality and to improve the soil nutrient balance [9–11].

The adoption of cover crops has increased over time. In North America, farmers reported sowing 15.4 million acres of cover crops in 2017, a 50% increase compared to the 10.3 million acres reported in 2012 [12]. Similarly, in Argentina, the cover crop adoption rate by farmers increased from 4% to 19% during the period 2014–2020 sowing 352,000 ha nationwide in 2020 [13]. The inclusion of cover crops is one of the most promising avenues for conservation management with a focus on improving carbon (C) cycling and N dynamics in our less diversified farming systems [14–17]. Cover crops are grown between two cash crops to capture available resources (such as water, radiation, and nutrients) during this period [18]. Other benefits related to cover crops include the intensification of the agricultural system (adopting more than one crop per year), and the contribution of N from leguminous cover crops via biological N fixation [19]. After cover crops are terminated, the N derived from crop residues can be utilized by the following cash crop via the decomposition of N-rich tissues [14,20], pointing cover crops as an alternative to replace or reduce the use of N fertilizers [21]. Although several studies reported benefits of employing cover crops in agricultural systems [17,22,23], farmers expressed dissimilar responses regarding the capability of cover crops to reduce the N fertilizer requirements [24–26]. Therefore, additional research on this topic is required to provide useful and actionable information to farmers on the potential benefits of cover crop inclusion.

In conservation agriculture, the use of hairy vetch (*Vicia villosa* Roth.) as cover crop is increasing [27], especially in humid to sub-humid regions. Hairy vetch is a good option as a cover crop due to i) high biomass production (in the order of 4–5 Mg ha^{-1}, [28]), ii) low C/N ratio (<25/1) of its residues, which facilitates net mineralization [29], and iii) ability to fix atmospheric N, which on average represents 60% of the total accumulated N [30]. Furthermore, hairy vetch biomass N content increases proportionally with biomass growth, resulting in an increased N contribution to subsequent cash crops [31,32]. These benefits are especially relevant for high N input requirement crops such as maize (*Zea Mays* L.) [33], heavily dependent on N fertilization [6]. Numerous studies have examined the yield effect of the inclusion of legumes as cover crops before maize [34–37], however no consistent effect was determined. Ref. [37] reported greater maize yields when employing hairy vetch as cover crop. Similarly [38], obtained maize yield increase with hairy vetch predecessor and low fertilizer N rates (0–60 kg ha^{-1}). On the other side, several other studies reported lack of effect or even a decrease in maize yield following hairy vetch [34–36]. These inconsistent results highlight the need for a more global synthesis analysis to quantify changes in maize yield after hairy vetch as a winter cover crop.

Meta-analysis allows testing hypotheses that cannot be answered by a single study [39]. Unlike other systematic reviews, it summarizes quantitative evidence of several experiments to obtain estimates, considering error sources [40]. Meta-analytic estimates often have the necessary statistical power to verify the significance of an effect when it is not possible in primary studies, especially when the effect is small [41]. Refs. [39,42] evaluated the effects of legume cover crops on maize yield in the United States and Canada, reporting a positive yield impact under lack of N fertilization. Ref. [43] demonstrated that legume cover crops improved the yield of the main crops, including maize, sorghum (*Sorghum bicolor* L. Moench), and rice (*Oryza sativa* L.). In addition, these yield advantages diminish with increasing rates of N fertilizers and in low-yield environments. Although, previous systematic reviews have pointed out cover crop benefits on successor crop yields utilizing meta-analytic methods, a crop-specific synthesis-analysis of hairy vetch inclusion as a cover crop on successor maize yield has not been reported yet.

This research hypothesized that there is an overall positive maize yield response to hairy vetch and performed a meta-analysis with the main goal of better understanding the impact of including hairy vetch in the rotation as maize predecessor. The specific objectives of this study are to i) quantify maize yield response with hairy vetch as previous crop, ii) assess hairy vetch influence on the yield of fertilized and non-N fertilized maize, and iii) explore the impact of tillage and environment factors on maize yield response to hairy vetch.

2. Material and methods

2.1. Data collection

A literature search was performed employing the scientific databases "Web of Science" (https://www.webofscience.com) and "Scopus" (https://www.scopus.com). The dataset used in this meta-analysis is part of a larger search and crop data collection that includes hairy vetch and numerous cash crops, where the dataset only corresponding to maize was selected for this study. The following search equation was applied to the title, abstract, and keywords of the publications: ("Hairy vetch" OR "Vicia villosa" OR "cover crop" OR "service crop") AND ("biomass" OR "yield") AND ("cereal" OR "legume" OR "crop" OR "soybeans" OR "maize" OR "corn" OR "sorghum"). The term "corn" was included in the search due to extensive use, however "maize" is used in this study to refer to *Zea mays* L. Keywords "cover crop" and "service crop" allowed to include publications that did not mention "Hairy vetch" or "Vicia villosa" in title, abstracts and keywords, but did include them in full text. The search was also constrained by journal articles and limited to agronomy, crops, and environmental sciences. The reference equation was checked in previous meta-analyses on the topic [39,42,44].

2.2. *Eligibility criteria*

The selection process was carried out using the R package *revtools* [45] in R software [46]. 5262 studies published between 1965 and September 2022 were identified from the databases (Fig. 1). The first step was to filter duplicated studies, resulting in the exclusion of 1445 articles. To keep relevant publications, the second step involved a title screening, wherein titles meeting the search keywords were selected, leading to the exclusion of 3090 studies. The third step was to filter by abstract, manuscripts had to meet at least one *eligibility criteria,* i) hairy vetch biomass production at the end of the season (absolute values), ii) maize grain yield (absolute values), and iii) report a treatment with hairy vetch and a control treatment without hairy vetch in the experimental design. A total of 607 papers were removed by this step. Finally, publications were manually selected based on their full text, retaining only the maize studies (excluding 78 articles) and those meeting all the *eligibility criteria* (excluding a further 19 articles). In October 2022, 23 papers were retained in this last screening.

The study selection method involved the review of titles and abstracts by one review author, MPR. If necessary, inconsistencies were discussed until a consensus was reached with the other authors, including JV, AJPC, AAC, and IAC. Two review authors, MPR and JV, then independently selected full-text articles for inclusion. In case of disagreement, a consensus on inclusion or exclusion was reached through discussion, and if necessary, a third author, IAC, was consulted.

A step of data filtering, and quality check was executed. A model was fitted considering all observations (n = 147) of 23 selected articles. First, a sensitivity analysis carried out using the leave1out function from the R package *metafor,* showed that a few observations introduced undesirable residual heterogeneity into this model [47] (Fig. S1). Secondly, an inspection of Cook distances and hat

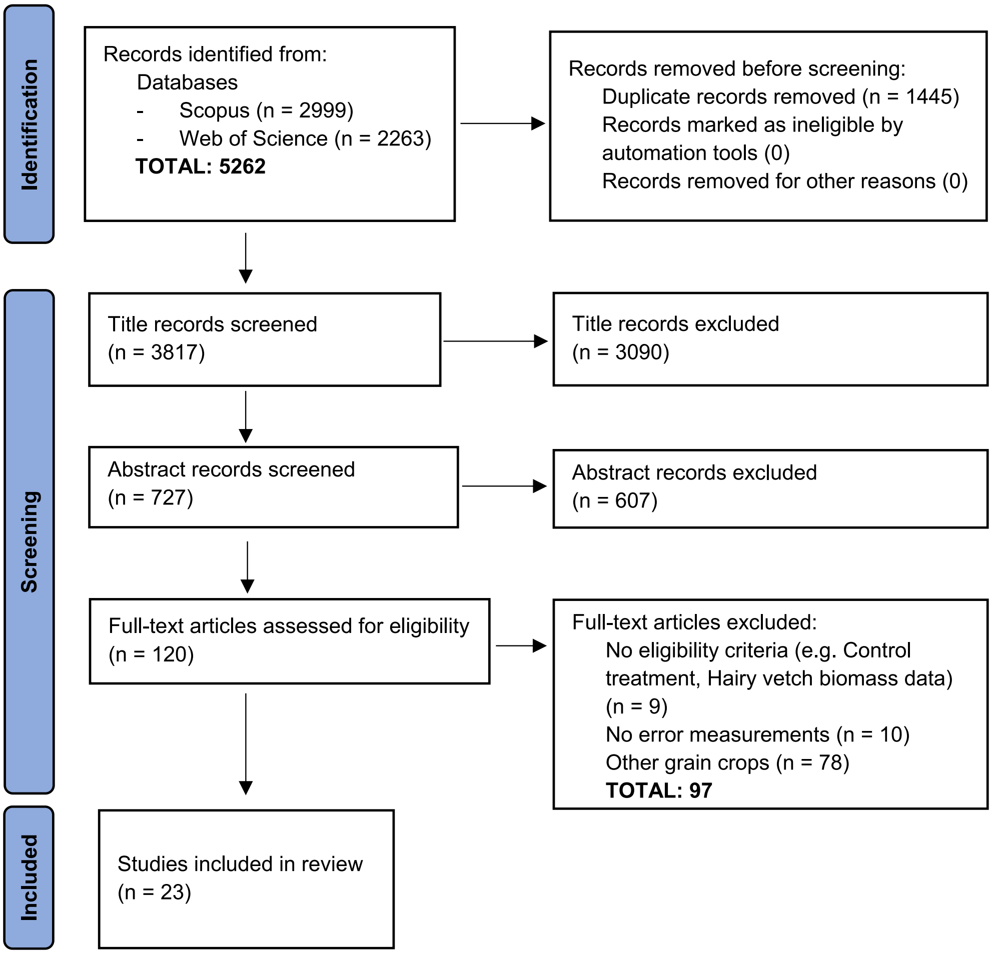

Fig. 1. Flow diagram describing the number of papers collected and various stages of filtering and selection.

values revealed that those similar observations presented high values, outliers, and leverage points. Lastly, when revising the original source (paper), those observations within each publication reported crop failure, confounding the effect of the cover crop on maize yields were deleted (one observation from Ref. [48] and one observation from Ref. [49]). Other studies [50,51] showed a residual heterogeneity but were not excluded as they did not report in the published manuscript any experimental problems. Finally, the total count remained at 23, as there was no need to completely exclude any publication, and the total number of observations was 145 (Fig. 1). All selected experiments were performed under field conditions. Table 1 describes the main characteristics of these studies.

2.3. Data extraction

For each selected publication, maize yield means, error measurements, and the number of repetitions were extracted to calculate the effect sizes. Error measures such as standard error (SE), confidence intervals (CI), coefficient of variation (CV), and mean squared error (MSE) were transformed to standard deviation (SD) [40]. The MSE estimates from balanced studies reporting means and post hoc letter results were obtained using the *MSE FindR* web application [52]. Additional information such as hairy vetch N content, N

Table 1
Description of the publications selected for the analysis. The ID refers to an identification number, citation include the first author and year of publication, year of study refers to the range of years when the experiment took place.

ID	Citation	Country	Year of study	N rate kg ha^{-1}	Experimental design	Main topics -keywords
1	Carciochi et al., 2021a	Argentina	2021	0; 50; 100; 200	Split split plot in randomized complete block	Cover crop effect in N management and maize yield. N diagnostics methods
2	Carciochi et al., 2021b	Argentina	2017–2018	0; 150	Split plot in randomized complete block	Sulfate, Nitrate, Chlorophyll meter reading, Oat, Hairy vetch
3	Spargo et al., 2016	USA	2009–2010	0; 45; 90; 180; 270	Split plot	Organic amendments, Cover crop effect, N dynamics
4	Drinkwater et al., 2000	USA	1993–1994	224	Randomized complete block	Mixed-tillage rotations, nitrogen mineralization, organic agriculture, vetch
5	Rosa et al., 2021	USA	2016–2018	40; 47; 106; 125	Randomized complete block	Cover crops, maize, soil water, weed suppression
6	Pott et al., 2021	Brazil	2014–2016	0; 60; 120; 180; 240	Factorial in randomized complete block	Vicia villosa effect, maize N uptake, yielding environments
7	Wittwer and Heijden, 2020	Switzerland	2012–2015	45; 90	Strip split plot	Cover crops for ecological intensification. Drone imagery
8	Power et al., 1991	USA	1982–1984	0; 62	Randomized complete block	Dryland maize production. Hairy vetch impact on N and soil water content
9	Decker et al., 1994	USA	1986–1988	0; 45; 135; 202	Split plot in randomized complete block	Legume cover crop effect. No till maize. Soil water content. N rate
10	Crespo et al., 2022	Argentina	2013–2015	0; 120	Split split plot in randomized complete block	Cover crops, maize nitrogen nutrition, water availability, termination date
11	Bracey et al., 2022	USA	2017–2019	[a]	Randomized complete block	Integrated cropping system. Soil nutrients. Cover crops dual-use
12	Dozier et al., 2017	USA	2013–2015	190	Split split plot Latin square	Tillage, cover crop effect. Soil properties. Crop production
13	Starovoytov et al., 2010	USA	2008	–	Split plot in randomized complete block	Nutrient pollution. Straw residue. Vetch N retention. Maize cropping systems
14	Pittman et al., 2020	USA	2016–2017	135	Split split plot in randomized complete block	Cover crop residue. Weed suppression effect. Maize and soybean
15	Singh et al., 2022	USA	2016–2019	222	Split plot in randomized complete block	Cover crops. Landscape position. Maize - soybean production
16	Parr et al., 2011	USA	2009–2010	–	Split plot in randomized complete block	Nitrogen dynamics. Cover crops effect on maize. Termination date
17	Koger and Reddy, 2008	USA	2002–2003	202	Split split plot in randomized complete block	Economic analysis, weed control. Cover crops. Integrated weed management
18	Bollero and Bullock, 1994	USA	1991–1992	0; 90; 180; 270	Split split split plot in randomized complete block	Cropping systems. Cover crops feasibility. Planting date, tillage. Sorghum, maize
19	Severini et al., 2021	Italy	2017–2018	40	Factorial in randomized complete block	Cover crops economic viability. Organic farming. Nitrogen availability
20	Reddy and Koger, 2004	USA	2002–2003	202	Split plot in randomized complete block	Live and killed hairy vetch. Weed control. Maize yield
21	Yenish et al., 1996	USA	1992–1993	65; 70; 76	Split plot in randomized complete block	Cover crops effect on Weed control. Termination method. No-till corn
22	Huntington et al., 1985	USA	1982	100	Split plot in Randomized complete block	Cover crop N supply. No till maize. Demand - supply synchronization
23	Vaughan et al., 2000	USA	1995–1996	0; 75; 150; 225; 300	Split split plot in randomized complete block	Tillage system. Cover crop N availability. Maize yield

[a] Nitrogen (N) application reported. N rate not specified.

fertilization on maize, tillage, coordinates, sowing and termination date of hairy vetch, sowing and harvest date of maize was recorded. The data presented as figures was extracted employing the R package *juicr* [53]. Two review authors (MPR and JV) extracted the data, performed necessary transformations, and any discrepancies were resolved by discussion.

The variables of interest are reported in Table 2. Descriptive statistics such as mean, minimum and maximum were calculated for each variable of interest. ID numbers 1, 7, 12, 14, 17, 20, and 23 indicated a split-plot arrangement with hairy vetch treatment as main plot (Table 1). Therefore, the mean, minimum, and maximum of hairy vetch biomass in these studies showed the same value.

2.4. Calculations

Maize yield response to hairy vetch as a previous cover crop was calculated as the natural logarithm of the response ratio between maize yield treatment with hairy vetch as predecessor ($\mathrm{Mz}_{\mathrm{hv}}$) and maize yield without hairy vetch as predecessor ($\mathrm{Mz}_{\mathrm{control}}$) [Eq. (1)]. The natural logarithm is used since it linearizes the metric, treating deviations in the numerator the same as deviations in the denominator. The log ratio is affected equally by changes in either numerator or denominator. Furthermore, the distribution of the natural logarithm of the response ratio is much more normal in small samples than that of the response ratio [40]. The response ratio (*RR*) was expressed as a percentage of change [Eq. (2)] to facilitate interpretation.

$$x_{i(j)} = \ln(RR) = \ln\left(\frac{\overline{\mathrm{x}}_{Mz_{hv}}}{\overline{\mathrm{x}}_{Mz_{control}}}\right) \quad [1]$$

$$Effect\ size(\%) = RR(\%) = \left[exp^{x_{i(j)}} - 1\right] * \ 100 \quad [2]$$

where $x_{i(j)}$ is the natural logarithm of hairy vetch effect size for the i th observation within the j th study. $\overline{\mathrm{x}}$ is the mean maize grain yield, Mz_{hv} is maize yield treatment with hairy vetch and $Mz_{control}$ is maize yield treatment without hairy vetch as prior cover crop. Effect sizes were weighted ($W_{i(j)}$) according to [Eq. (4)], which is the inverse of the pooled sampling variance $v_{i(j)}$ [Eq. (3)] between the two groups, as follows:

$$v_{i(j)} = \frac{\left(SD_{Mz_{hv}}\right)^2}{n_{Mz_{hv}} \times \left(\overline{x}_{Mz_{hv}}\right)^2} + \frac{\left(SD_{Mz_{control}}\right)^2}{n_{Mz_{control}} \times \left(\overline{x}_{Mz_{control}}\right)^2} \quad [3]$$

$$W_{i(j)} = \frac{1}{v_{i(j)}} \quad [4]$$

Table 2

Summary descriptive for each study of the mean maize grain yield after hairy vetch ($\mathrm{Mz}_{\mathrm{hv}}$), control without hairy vetch ($\mathrm{Mz}_{\mathrm{control}}$), hairy vetch dry matter (DM), and hairy vetch nitrogen content (N); ID refers to a study identification number, n° is the number of observations, sd corresponds to the mean of the standard deviation of each observation, Min and Max are the minimum and maximum maize yield and hairy vetch dry matter values reported for each study. Maize yield values refer to the mean considering N fertilized and non-N fertilized maize.

Maize										Hairy vetch			
ID	n°	$\mathrm{Mz}_{\mathrm{hv}}$	$\mathrm{sd}_{\mathrm{hv}}$	$\mathrm{Min}_{\mathrm{hv}}$	$\mathrm{Max}_{\mathrm{hv}}$	$\mathrm{Mz}_{\mathrm{control}}$	$\mathrm{sd}_{\mathrm{control}}$	$\mathrm{Min}_{\mathrm{control}}$	$\mathrm{Max}_{\mathrm{control}}$	DM	Min	Max	N
		Mg ha^{-1}				**Mg ha^{-1}**				**Mg ha^{-1}**			**kg ha^{-1}**
1	4	10.4	0.7	8.5	11.6	9.8	0.9	7.5	11.6	2.5	2.5	2.5	69
2	12	8.5	0.8	5.7	10.4	7.3	0.5	4.6	9.7	3.6	2.7	5.1	126
3	10	11.7	0.8	7.7	14.4	11.0	1.2	7.3	13.1	3.1	1.6	4.6	107
4	2	8.5	0.5	7.9	9.1	8.6	0.3	8.6	8.6	3.1	2.9	3.3	150
5	1	7.2	1.0	7.2	7.2	8.7	0.4	8.7	8.7	0.8	0.8	0.8	–
6	8	12.9	0.5	11.8	13.7	12.0	0.5	10.7	13.1	5.0	4.8	5.3	207
7	12	9.5	0.9	8.0	11.3	8.0	1.0	6.3	10.0	3.3	3.3	3.3	142
8	12	2.2	0.4	0.3	6.3	2.7	0.4	1.0	5.9	0.8	0.5	1.4	41
9	7	7.9	1.2	6.3	9.2	6.8	1.0	4.7	7.9	4.0	2.7	7.2	152
10	12	8.8	0.5	7.7	10.4	7.9	0.6	6.7	9.5	2.2	0.6	3.7	73
11	1	11.5	2.5	11.5	11.5	1.5	2.5	11.5	11.5	1.8	1.8	1.8	51
12	3	11.8	4.7	11.7	11.9	12.0	4.7	11.4	12.5	0.2	0.2	0.2	–
13	1	8.5	1.4	8.5	8.5	7.8	2.2	7.8	7.8	4.3	4.3	4.3	160
14	2	1.7	1.1	1.4	2.1	1.3	1.1	0.8	1.8	3.7	3.7	3.7	146
15	3	9.3	4.9	7.2	10.7	8.3	1.2	7.3	9.8	2.7	1.9	3.4	57
16	28	4.0	1.2	0.8	8.5	3.9	1.2	1.1	6.2	4.7	2.2	6.6	155
17	3	10.8	0.6	10.4	11.4	9.0	0.6	9.0	9.0	2.3	2.3	2.3	–
18	2	7.3	0.5	6.8	7.8	6.9	0.5	6.7	7.1	2.2	1.9	2.6	101
19	7	2.8	0.9	1.7	4.2	4.0	0.9	2.3	5.2	6.1	4.4	8.3	223
20	9	9.6	0.9	7.5	11.8	10	0.9	7.0	12.1	2.3	2.3	2.3	–
21	1	2.5	1.7	2.5	2.5	2.9	1.7	2.9	2.9	2.2	2.2	2.2	–
22	1	9.1	0.8	9.1	9.1	6.6	0.8	6.6	6.6	3.2	3.2	3.2	125
23	4	10.6	1.6	8.5	11.5	7.8	1.6	6.4	9.1	5.6	5.6	5.6	234

where *SD* is standard deviation of each observation, and *n* indicates the number of observations of each study for the maize yield preceded by hairy vetch (nMz_{hv}) and maize yield not preceded by hairy vetch ($nMz_{control}$) groups, respectively. Then, observations outcomes (*i*) were grouped at study level (*j*).

2.5. Data analysis

The effect sizes were estimated using random-effects model analysis in R package *metafor* [47]. The meta-analytic model attributes a weight [Eq. (4)] to each study, which is a measure of statistical precision that increases with less variance [40]. Heterogeneity across studies that cannot be attributed to experimental error was represented by I^2 statistic [54]. When the heterogeneity between studies was greater than 75%, mixed effects models were analyzed to further explore variability drivers, employing moderator variables [55]. Egger's test [56] and funnel plot [47] were used to assess publication bias in the meta-analyses. Bias assessment was carried out by one review author, MPR, and any discrepancies were resolved by discussion to reach consensus between the review authors. Forest plots and scatter plots were created to provide a graphical overview of the analyzed data [47].

The following meta-analytical estimations were carried out; firstly, an overall analysis of hairy vetch effect size was performed without differentiating N fertilizer rates on maize. Secondly, a categorical division was formed diving the total of observations into two maize N fertilization subgroups, i) without N fertilization (60 observations collected from 9 articles), and ii) with N fertilization (88 observations collected from 20 articles). Nitrogen fertilization corresponds to average levels of 130 kg ha^{-1} with a range from 40 to 270 kg ha^{-1}. A random effects model was fitted for each N fertilization subgroup separately. Third, within each N fertilization subgroup an ANOVA using the anova.rma function was conducted entering two categorical variables as moderators i) no-tillage and ii) conventional tillage before maize sowing.

Meta-regression analyses were performed including continuous variables as moderators within each N fertilization subset. Fallow length (days) was included as a management variable. Accumulated rainfall (mm) 60 days before and 60 days after maize sowing, sand

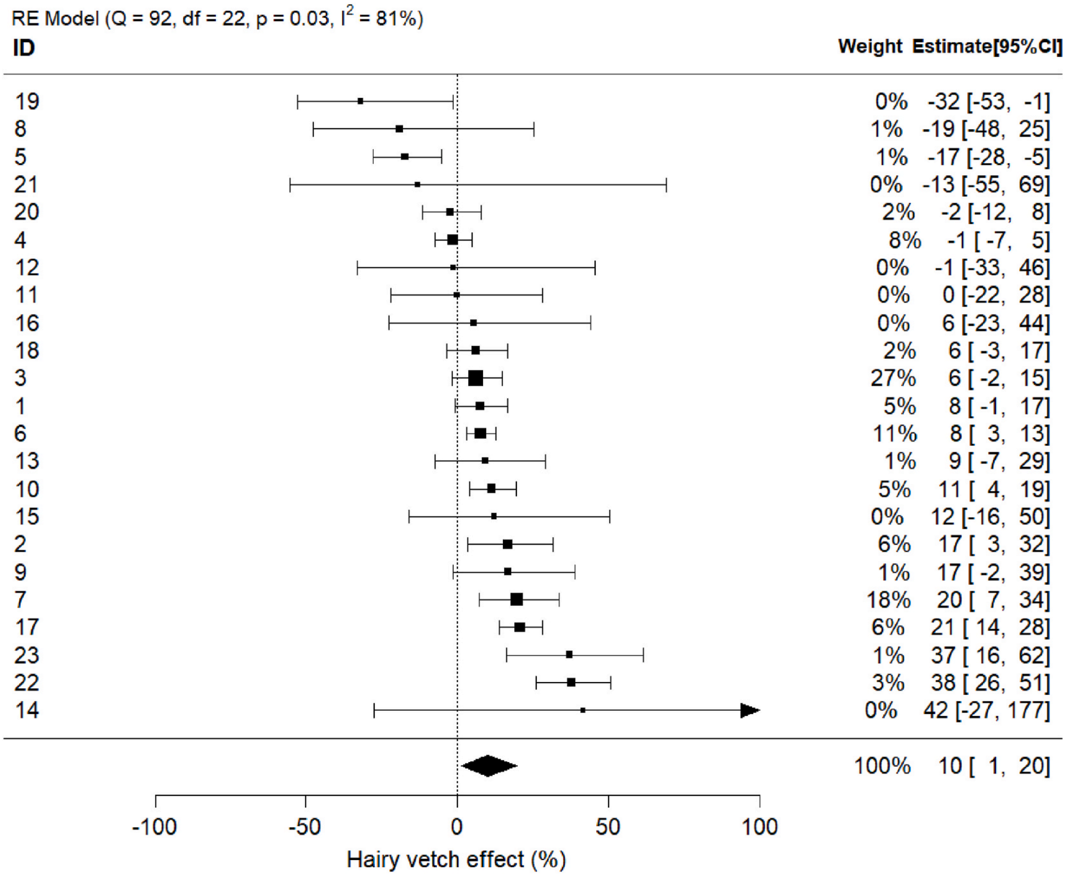

Fig. 2. Forest plot summarizing the effect of hairy vetch as previous cover crop on maize (Mz) yield. ID refers to a study identification number. Effect sizes and 95% confidence intervals (CI) are expressed as a hairy vetch (hv) effect ratio (percentage of grain yield variation in $Mz_{hv}/Mz_{control}$). Square symbols represent point estimates and whiskers depict their respective 95% CI. The weight of each study is expressed as a percentage of the overall model and illustrated by the size of box and the thickness of whiskers. RE = random effects model, Q = Cochran's Q test statistic; I^2 = I-square statistic.

(g kg^{-1}), and clay (g kg^{-1}) at 0–5 and 5–15 cm depth were included as environmental and soil variables. The data on rainfall and soil characteristics were not provided by all the selected studies. Therefore, *soilDB* [57] and *chirps* package [58] were used to obtain clay, sand, and rainfall data to perform the analyses.

Finally, a case study was carried out to analyze the interaction among three variables i) organic matter content, ii) fertilizer N rates on maize, and iii) N accumulation in hairy vetch, in relation to maize yield response to hairy vetch. Due to limited data availability across all studies, a subset of the entire database containing these three variables was selected (n° of studies = 7, n° of observations = 31). A division into thirds was performed to determine a subgroup analysis for both fertilizer N rates and N accumulation in hairy vetch (breaks in 33.3% and 66.7% of the total distribution). Additionally, a division into two groups was applied for organic matter based on visualization of the threshold (4%), as the data showed a bimodal distribution. It is noteworthy that, due to the absence of standardized soil sampling procedures, soil depth determinations from the literature were collected within the range of 0–15 cm to 0–30 cm.

3. Results

Descriptive statistics indicated that Mz_{hv} showed an average yield of 8 Mg ha^{-1} and varied over a wide range between studies from 2 to 13 Mg ha^{-1} with a standard deviation of 1 Mg ha^{-1} (Table 2). The mean yield of $Mz_{control}$ was 7 Mg ha^{-1} ranging widely between 1 and 12 Mg ha^{-1} and a standard deviation of 1 Mg ha^{-1}. The average dry matter (DM) of hairy vetch was 3 Mg ha^{-1} with values from 0.2 to 6 Mg ha^{-1}. Based on available observations of hairy vetch N content, the mean of N was 129 kg ha^{-1} ranging from 41 to 234 kg ha^{-1} of produced biomass at the end of the season.

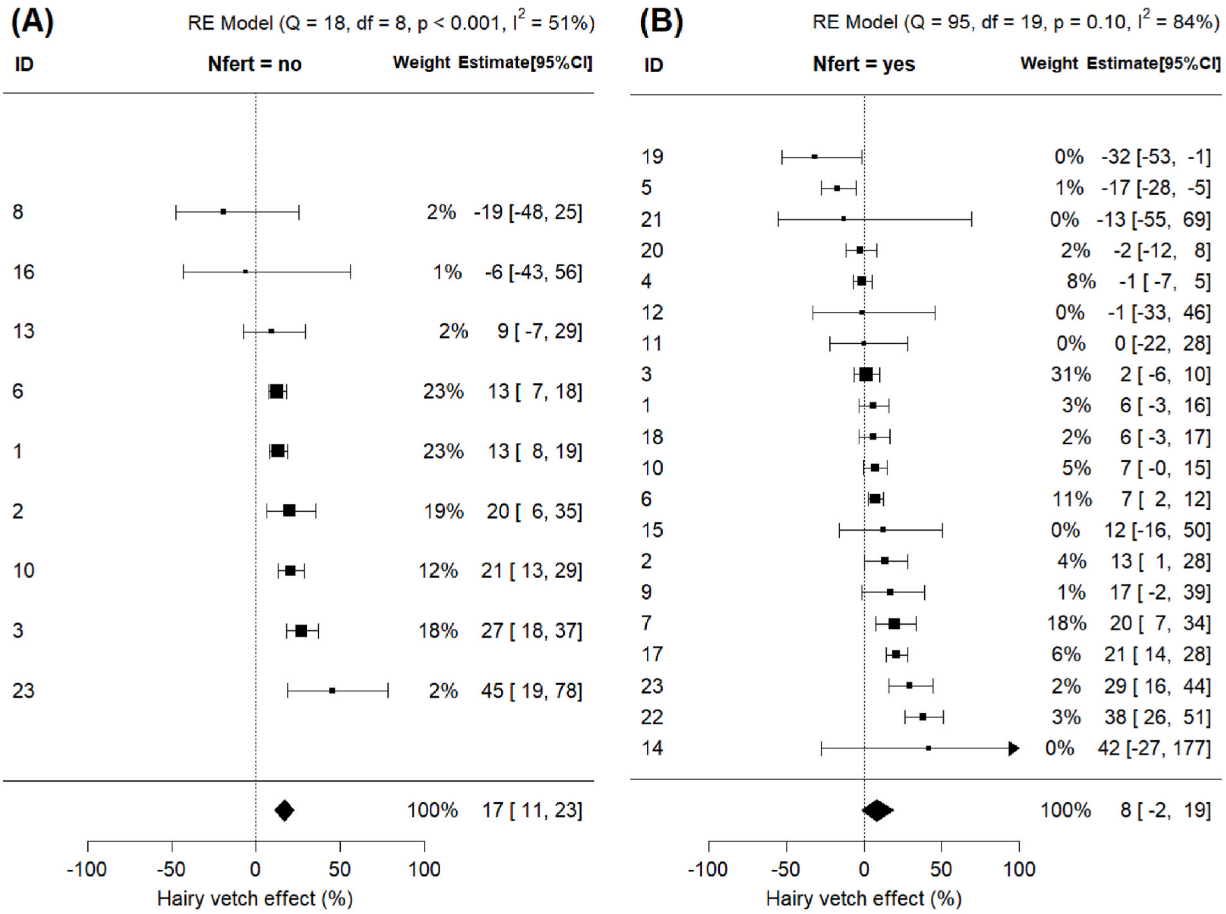

Fig. 3. Forest plot for subset analysis on hairy vetch effect sizes as a previous cover crop for (A) maize (Mz) without nitrogen fertilization and (B) maize with nitrogen fertilization. Effect sizes and 95% confidence intervals (CI) are expressed as a hairy vetch (hv) effect ratio (percentage of grain yield variation in $Mz_{hv}/Mz_{control}$). Nitrogen fertilization corresponds to average levels of 130 kg ha^{-1}. Square symbols represent point estimates and whiskers depict their respective 95% CI. The weight of each study is expressed as a percentage of the model and illustrated by the size of box and the thickness of the whiskers. RE = random effects model, Q = Cochran's Q test statistic; I^2 = I-square statistic.

3.1. Hairy vetch effect on maize yield

The overall analysis of the dataset (i.e., without discriminating between N and non-N-fertilized maize) showed a significant heterogeneity on the hairy vetch effect size over the following maize yield ($p < 0.001$) (Fig. 2). The I^2 statistic was 81%, indicating large dissimilarity between studies. Most studies ($n = 14$) showed a non-significant yield impact, characterized by high variability on the effect and representing about half of the weights (~49%) on the overall effect estimation. About a third of the studies ($n = 7$) manifested a positive effect on maize yield ranging from 8 to 38%, representing ~50% of the weights. Finally, only two studies showed a negative impact (−32% and −17%) on maize yields, which represented the smallest portion of the weights (~1%) on the overall effect estimation. The outcomes from the Egger's test did not indicate statistical significance in terms of publication bias (95% CI = −1 to 25; $p = 0.54$). The funnel plot is displayed in Fig. S2.

3.2. Nitrogen fertilization

When N fertilization treatments were analyzed separately, the I^2 statistic indicated significant variability between studies, yet the effect of hairy vetch resulted more consistent for non-N fertilized maize ($I^2 = 51\%$) compared to N-fertilized maize ($I^2 = 84\%$, Fig. 3). Most studies ($n = 6$) manifested a positive effect on non-N fertilized maize yield ranging from 13 to 45%, representing ~95% of the weights on the hairy vetch effect estimation (Fig. 3A). Only three studies showed non-significant yield impact, which represented ~5% of the weights. Lastly, no negative impact on non-N fertilized maize yield was obtained. For N-fertilized maize, about half of the studies ($n = 12$) showed a non-significant yield effect, pointing out a high variability between studies representing ~55% of the weights on the hairy vetch effect estimation ($p = 0.10$, Fig. 3B). A third of the studies ($n = 6$) indicated a positive maize yield impact ranging from 7 to 38%, showing ~44% of the weights. Finally, two studies reported negative effects (−32 and −17%), with the lowest weights (~1%) on the effect estimation. Egger's tests showed no publication bias for non-N fertilized maize (95% CI = −1 to 36; $p = 0.55$), and N-fertilized maize (95% CI = −4 to 17; $p = 0.45$).

3.3. Comparison between conventional tillage and no-tillage systems

Tillage systems were analyzed within each maize N fertilization subset as categorical variables (Fig. 4A and B) to explore additional reasons for heterogeneity in maize response. There was no evidence of publication bias for N-fertilized ($p = 0.52$) and non-N fertilized subset ($p = 0.95$). The outcomes for the non-N fertilized subgroup were characterized by low heterogeneity ($I^2 = 14\%$) compared to the N fertilized ($I^2 = 85\%$). Within the non-N fertilized subset, no-tillage indicated an increase on maize yield response of 14% ranging from 10 to 19% (Fig. 4A). Expressed in Mg ha^{-1} of yield gain, this increase represented 0.9 Mg ha^{-1} ranging from 0.7 to 1.3 Mg ha^{-1} (Fig. S4). Likewise, conventional tillage before maize sowing showed an even greater maize yield response than no-tillage reaching 31% with a range of 23–41%. The yield gain resulted in 1.8 Mg ha^{-1} and ranged from 1.3 to 2.4 Mg ha^{-1} (Fig. S4). In contrast, within the maize N fertilized subset, tillage and no-tillage categories entered were not able to explain the variability reported between studies ($p = 0.60$, Fig. 4B).

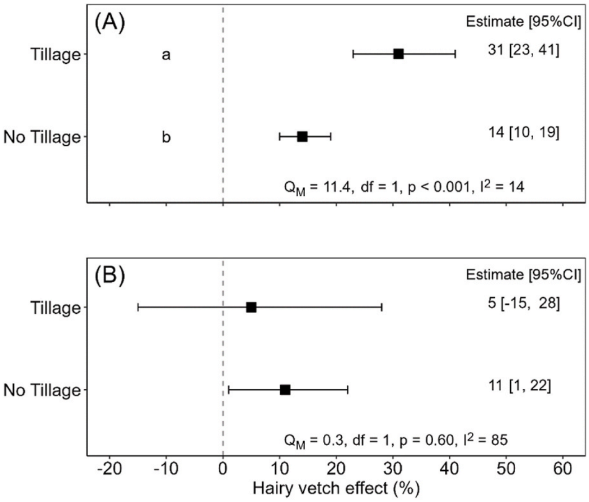

Fig. 4. Impact of hairy vetch on maize (Mz) yield response according to (A) conventional tillage ($n = 3$) and no-tillage ($n = 7$) systems without nitrogen fertilization on maize, and (B) conventional tillage ($n = 4$) and no-tillage ($n = 16$) systems with nitrogen fertilization on maize. Nitrogen fertilization corresponds to average levels of 130 kg ha^{-1}. Effect sizes and 95% confidence intervals (CI) are expressed as a hairy vetch (hv) effect ratio (percentage of grain yield variation in $Mz_{hv}/Mz_{control}$). Square symbols represent point estimates and whiskers depict their respective 95% CI. Q_M = Cochran's Q test statistic for moderators; I^2 = I-square statistic. n = number of studies within categories. Different letters indicate significant differences between effect sizes at $p \leq 0.05$.

3.4. Relationship between hairy vetch effect, environmental conditions, and cover crop management

For both the non-N fertilized and N fertilized maize subsets, the assessment of the fallow length did not reveal a significant influence of hairy vetch on maize yield. The period between hairy vetch termination date and maize sowing manifested an $I^2 > 80\%$ suggesting variability among experiments (Fig. 5A and B). Furthermore, the analysis of the accumulated rainfall 60 days before and 60 days after maize sowing failed to explain the effect of hairy vetch and exhibited significant heterogeneity ($I^2 > 90\%$, Figs. S5A–D). Additionally, the analysis of the soil characteristics showed a slight decrease in maize response of 0.03% per g kg^{-1} of clay at 0–5 cm depth ($I^2 = 17\%$, Fig. S6A). The other features including sand at 0–5 cm depth, as well as clay and sand at 5–15 cm depth did not yield consistent results concerning the impact of hairy vetch on maize. These factors exhibited an I^2 greater than 80% in both maize N fertilization subsets (Figs. S6 and S7).

3.5. Case study

The N accumulation in hairy vetch in the range of 95–150 kg N ha^{-1} resulted in maize yield responses from 9 to 36% when no N was applied (0 N) and from 13 to 39% with fertilizer N rates below 120 kg N ha^{-1} (<120 N) (Fig. 6B). In contrast, when N accumulation for hairy vetch was below 95 kg ha^{-1} (Fig. 6A) or exceeded 150 kg ha^{-1} (Fig. 6C), maize yield was not impacted for the analyzed fertilizer N rates. The variability (I^2) was 82% and 92% for N accumulation for hairy vetch of <95 kg ha^{-1} and >150 kg ha^{-1}, respectively. Notably, I^2 decreased to 60% within the range of 95–150 kg ha^{-1} (Fig. 6B).

Egger's test did not indicate publication bias for organic matter levels and hairy vetch dry matter subsets ($p > 0.05$) (Fig. S3). There was no significant interaction between soil organic matter levels and fertilizer N rates in relation to maize yield response to hairy vetch ($p = 0.98$) (Fig. 7A). Additionally, N accumulation in hairy vetch did not demonstrate an interaction with organic matter in this study ($p = 0.19$) (Fig. 7B).

4. Discussion

This meta-analysis provides new insights of hairy vetch cover crop effect on maize yield across diverse regions, indicating a general positive response to low N rates applied or even no N fertilization for the following maize. In addition, to the extent of our knowledge the range of variation in maize yield response has not been documented before, and even for limitations of the published data major insights on main factors linked to this broad variation are still less known. This meta-analysis clearly points out the complexity behind the adoption of cover crops and the overall interaction of management and environmental factors on the response to this practice.

The importance of legume cover crops in their contribution to increase yield of following crops in the rotation has been documented in several studies around the globe [23,59–61]. As previously documented, the potential agronomic benefits could be classified into two groups, i) diversification [62,63] including the benefits to soil structure, soil biological activity, phosphorus availability, and reduction of pressure from diseases and weeds (e.g. Refs. [64–67]), and ii) those linked to N supply (so-called "nitrogen-effect", [68,69]). A meta-analysis comparing more broadly cereals and legumes [39] documented a similar effect with a high impact of legumes as cover crops on maize yield (37%) without N fertilization, but with the size of the effect reducing as N fertilization increases.

Current literature on hairy vetch response on maize yield can be dissected in those situations reporting either negative, neutral, or positive effects. For the first type of outcome, a decrease in yields from hairy vetch presence was mainly linked to i) less water available for maize due to hairy vetch consumption in semi-arid regions [70]; and/or ii) failure in hairy vetch killing methods causing competition with maize for resources such as soil moisture, nutrients, and light [71,72]. For the second type, neutral effects, non-limiting environments with optimal water and nutrient availability tend to present a less clear response of hairy vetch on maize yields [73,74]. Lastly, positive response on yield could be linked to i) improvements in soil N availability derived from hairy vetch residues decomposition (both above- and below-ground biomass) [75,76], and ii) enhancement on water infiltration with a consequent better water economy [77,78], with a more consistent effect under low fertility soils and reduced fertilizer N rates applied to maize

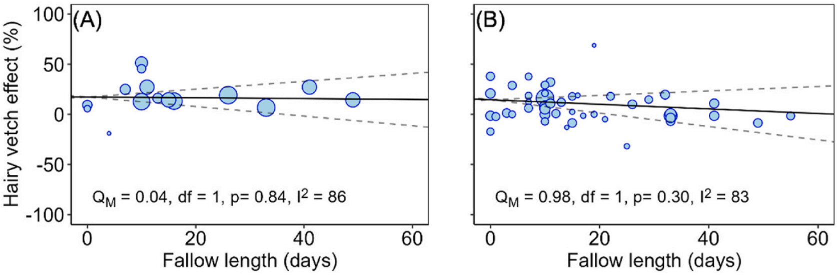

Fig. 5. Impact of hairy vetch on maize (Mz) yield response without nitrogen fertilization (a) and with nitrogen fertilization (b) for fallow length (days) between hairy vetch termination date and maize sowing. Hairy vetch effects are expressed as a hairy vetch (hv) effect ratio (percentage of grain yield variation in $Mz_{hv}/Mz_{control}$). Solid line represents meta-regression prediction and dashed line their respective 95% CI. Circles represent point estimates and are observations within selected studies. The weight of each observation is expressed as a percentage of the model and illustrated by the size of circles. QM = Cochran's Q test statistic for moderators; I^2 = I-square statistic.

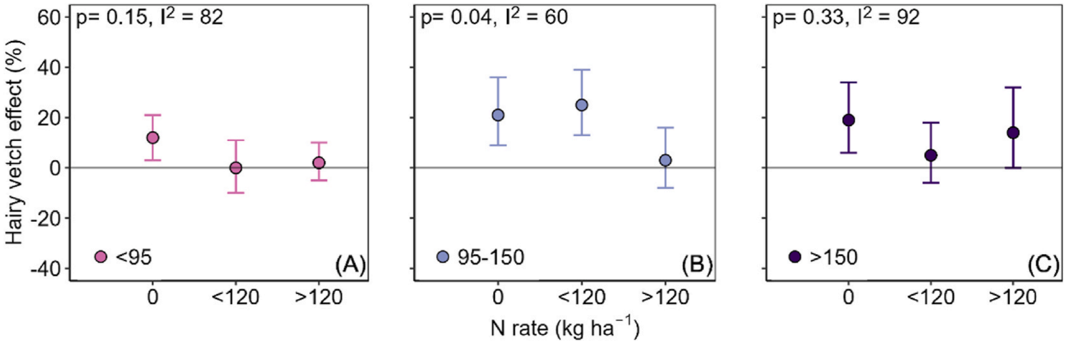

Fig. 6. Effect of hairy vetch on maize (Mz) yield across three categories of N accumulation in hairy vetch dry matter (kg N ha^{-1}) at the termination time (A) <95, (B) 95–150, and (C) >150, in relation to three categories of fertilizer N rates for maize (0, <120, and >120 kg N ha^{-1}). Effect sizes and 95% confidence intervals (CI) are expressed as a hairy vetch (hv) effect ratio (percentage of grain yield variation in $Mz_{hv}/Mz_{control}$). Circle symbols represent point estimates, and whiskers depict their respective 95% CI; I^2 = I-square statistic.

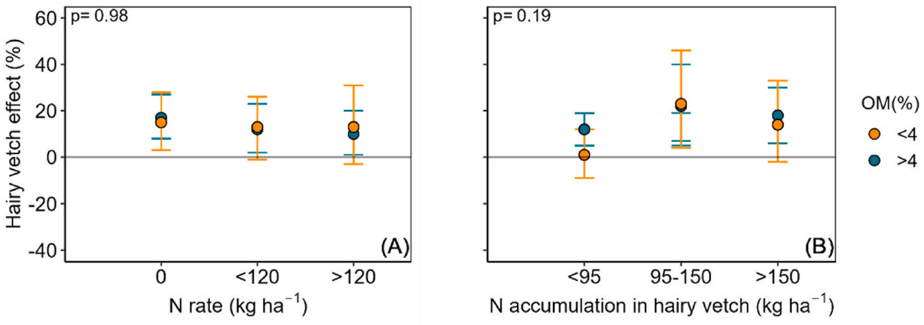

Fig. 7. Effect of hairy vetch on maize (Mz) yield for two categories of organic matter (OM) content (<4% or >4%) in relation to three categories of fertilizer N rates for maize (kg N ha^{-1}) (A), and three categories of N accumulation in the hairy vetch dry matter at the termination time (kg N ha^{-1}) (B). Effect sizes and 95% confidence intervals (CI) are expressed as a hairy vetch (hv) effect ratio (percentage of grain yield variation in $Mz_{hv}/Mz_{control}$). Circle symbols represent point estimates, and whiskers depict their respective 95% CI.

(below the optimal) [38].

The inclusion of cover crops in conjunction with a no-tillage system has demonstrated improvements in soil aggregation and nutrient retention over the long-term by preserving plant residue inputs and avoiding soil removal [79,80]. Consequently, these practices have led to significant enhancements in crop yields [81]. In contrast, conventional tillage practices can temporarily increase the N release from hairy vetch into the soil in plant-available forms, leading to a subsequent boost in crop yields [82–84]. However, the persistence of these positive effects may not persist over time due to aggregate breakdown and potential nutrient losses [85]. Additionally, it is worth highlighting not only the overall contribution of N but the importance of the synchrony affecting the N recovery on maize between N release from the cover crop residue (decomposition rate) and the rate of the crop N demand [9,86,87].

The N carryover from the hairy vetch to the subsequent maize appears to be a relevant factor supporting the positive effects reported in this meta-analysis and potentially assists in reducing the dependency on exogenous N-fertilizers [88]. Especially for legume cover crops such as hairy vetch, the contribution of N via N fixation process is closely related to the amount of cover crop biomass production [20,30]. Previous studies described increases in maize yield associated with a greater N accumulation of hairy vetch and N release for the next crop in the rotation [89]. The biomass production necessary to perceive an impact on yield was reported within the range of 3–5 Mg ha^{-1} and the N content of hairy vetch ranged from 100 to 120 kg ha^{-1}, consistent with the results of our study [38,50,90,91]. Likewise, multiple additional factors influence the overall contribution of N from hairy vetch such as the soil N supply during the cover crop growing season [23,92], the management of the hairy vetch and termination dates [93], maize growth and N demand [94], and the effectiveness on the legume-rhizobium interaction [95]. However, as previously documented, it is also important to highlight that legumes may provide additional (more elusive to quantify) benefits such as those previously termed as diversification effects. Lastly, although meta-analysis represents a step forward, more comprehensive research assessments of the soil-plant system (e.g., including N fixation, and soil N availability dynamics) are necessary to refine the understanding of hairy vetch effects on maize yields.

The main limitations of this meta-analysis are related to the small number of studies selected based on the current eligibility criteria, constraining the assessment of explanatory variables, and leading to a high unexplained heterogeneity among studies. This heterogeneity was noticeable in management factors, such as the fallow length period between hairy vetch termination and maize sowing. Soil fertility measures such as inorganic N available (NH_4^+-N and NO_3^--N) reported in the articles presented a lack of sampling standardization, which restricted its evaluation as a possible variable in this meta-analysis. Furthermore, large reported standard errors reflect in also large variability within the studies. Future studies should address the identification of environmental drivers such as soil, weather, crop, and management variables to better understand the major factors impacting the overall effect of hairy vetch on the following maize crop. Moreover, a detailed analysis of N rates is recommended to assess the effect of hairy vetch and N fertilization along with other edaphoclimatic factors. Lastly, it is critical to focus on the long-term impacts of hairy vetch on increasing maize production and the overall N contribution to agricultural systems.

5. Conclusion

This meta-analysis quantitatively summarizes hairy vetch effects on maize yield. While yield response to hairy vetch was more consistent when maize was not fertilized with nitrogen, a case study revealed that supplying N through hairy vetch in the range of 95–150 kg ha^{-1}, in addition to applying rates below 120 kg ha^{-1} on maize led to increase maize yields. These outcomes provided a more precise quantitative perspective. In non-N-fertilized maize, conventional tillage before maize sowing was related to a yield response to hairy vetch 16% higher than no-tillage. Nevertheless, no-tillage combined with cover crops provides an alternative management for reaching more long-term sustainable farming systems. It is noteworthy that maize yield response was characterized by high heterogeneity in our study, pointing out the complexity behind hairy vetch adoption and the interplay of environmental and agronomic factors. In summary, the results of this meta-analysis suggest the need for further comprehensive analysis and field studies, particularly emphasizing the N transfer from hairy vetch to maize, including soil N pools, N supplied by hairy vetch, and maize N application rates. Lastly, given the inclusion of diverse study regions in this analysis, these findings are highly encouraging for the global-scale integration of hairy vetch into agricultural systems, aligning with the growing adoption trend.

Data availability statement

The protocol has been registered at https://doi.org/10.17605/OSF.IO/SP97W in the Open Science Framework (OSF) repository. Related files are available in the figshare repository at https://doi.org/10.6084/m9.figshare.23792607.

CRediT authorship contribution statement

Maria P. Rodriguez: Writing – original draft, Visualization, Software, Investigation, Formal analysis, Data curation. **Joaquin Vargas:** Data curation. **Adrian A. Correndo:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Ana J.P. Carcedo:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Walter D. Carciochi:** Writing – review & editing. **Hernan R. Sainz Rozas:** Writing – review & editing. **Pablo A. Barbieri:** Writing – review & editing. **Ignacio A. Ciampitti:** Writing – review & editing, Supervision, Resources, Methodology, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare no conflict of interest. The paper contents have not been previously published nor are under consideration for publication elsewhere. All co-authors have contributed to the paper and have agreed to be listed as co-authors.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e22621.

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