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Do Cover Crops Increase Subsequent Crop Yield in Temperate Climates? A Meta-Analysis

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Abstract: Cover crops (CCs) are a promising strategy for maintaining and enhancing agroecosystem sustainability, yet CCs' effects on the subsequent crop yield are highly variable. To quantitatively synthesize the effects of CCs on subsequent crop yield, a meta-analysis of 672 observations collected from 63 recent studies (2015 to 2021) in temperate climates was conducted. Legume CC species increased subsequent crop yield significantly more than grass (by 14%), nonlegume broadleaves (by 7%), and mixtures (by 2%). Incorporation of CC residue into soil increased crop yield by approx. 15% compared to leaving the CC residue on the soil surface. Relative to the no-CC control, the adoption of grass and legume CC species in non-organic vegetable cropping systems enhanced crop yield by 14% and 19%, respectively. Likewise, crop yield with legume CCs in coarse and medium textured soil, and under high precipitation conditions (>700 mm), was significantly greater than the no-CC control by 18%, 4%, and 11%, respectively. Cover crops significantly increased vegetable crop yields and decreased the silage corn yield; however, grain corn, soybean, and winter wheat yield did not decrease with CC. Adoption of CC in no-tillage and plow tillage systems contributed to an increase in crop yield compared to the no-CC control. Our meta-analysis highlights that crop yield response to CC might become more robust when pedo-climatic conditions and agronomic factors are considered.

Keywords: catch crop; grain crop production; tillage; service crop; sustainable land management; vegetable production; best management practice

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1. Introduction

Global food security is one of the biggest challenges facing agriculture today. This challenge is further intensified because food production should focus not only on safe and high-quality food, but products must also be produced sustainably. Intensive conventional agricultural practices might contribute to enhancing crop productivity, yet a degradation in soil and environmental quality is observed with the use of heavy machinery, limited rotational diversity, and excessive inputs of agricultural chemicals [1,2]. Therefore, land management practices which sustain and improve crop productivity while minimizing the negative impacts on the environment are needed.

Cover crops (CCs), usually grown after the main crop harvest in summer/fall (Figure 1), are a land management strategy which provides numerous ecosystem services. Some of the beneficial services provided by CC are an increase in soil organic C [3], increase in soil N availability [4], increase in soil biodiversity [5], increase in soil aggregate stability [5–7], decrease in insect and disease infestation [8], and reduction in weed pressure [9]. Cover crops are also a promising option for enhancing the subsequent crop yield [3,4,10,11], which is a major factor driving farmers' decision making regarding CC adoption into cropping systems [9]. Cover crops impart benefits to subsequent crop yield via numerous mechanisms, such as increased availability of nutrients in the following growing season, reduced losses of N through immobilization, increased soil microbial activity, and a reduction in weeds [12,13]. Leguminous CC species, for instance, can biologically fix atmospheric N, thereby enhancing plant-available N and crop yield [14–16]. Likewise, a review by Blanco-Canqui et al. [5] and a meta-analysis by Bourgeois et al. [16] reported increases in crop yield with leguminous CC due to the positive impacts of legumes on soil N availability. Cover crop mixtures have also been recommended as a valuable strategy for increasing subsequent crop yields [15].

Figure 1. Comparison of cover crops planted in mid-August (foreground) and mid-September (mid-ground) with grain corn in the background at the Ontario Crops Research Centre—Ridgetown, Ontario, Canada. Photo taken on 29 October 2020 by Dr. Laura L. Van Eerd.

In contrast, several studies have reported either neutral or negative effects of CCs on crop yield [14,16–19]. Yield uncertainty with respect to CC use suggests that crop yield response to CCs varies across CCs (e.g., species type, termination time, amount of aboveground biomass, residue management), main crop (e.g., species, production system, tillage, amount of N inputs), and pedo-climatic conditions [9,14,18]. For instance, a meta-analysis by Alvarez et al. [17] reported that corn (*Zea mays* L.) grain yield decreased by 8% following the use of non-leguminous CC species, whereas soybean (*Glycine max* L.) yield was not impacted by CCs. Cover crop termination time impacts the subsequent crop yield response because timely termination of CC results in better synchronization between CC residue mineralization and crop nutrient uptake than early or late CC termination [9]. Additionally, the use of CC in reduced tillage (minimum and no-tillage) systems contributes to enhancing crop yield, possibly due to the decrease in disturbance of the soil and the increase in soil quality [20,21]. The enhanced soil quality found in reduced tillage systems is mainly attributed to addition of C inputs from crop residue, which increase soil microbial activity and community dynamics [20,21]. It has been reported that crop yield uncertainty following CC is one of the major challenges restricting CC adoption by growers [18]. Therefore, to accurately estimate the CC-induced effects on crop yield and to better inform decision making related to CC adoption, the impact of management factors contributing to yield uncertainty must be considered.

A meta-analysis was conducted to quantitatively assess crop yield response to CC in temperate climates. Meta-analysis is a powerful statistical method used to quantitatively summarize the results from multiple independent studies, evaluate the heterogeneity in the dataset, identify the potential sources of variability in the response parameter, and assess the magnitude of the effect size [22]. Cover crops' effects on crop yield in temperate climates have been reviewed previously [5,23,24], yet a handful of meta-analyses have compared the effects of CCs between crops, which might have provided meaningful insights into adoption strategies [9,13,17,18]. To our knowledge, very few meta-analyses have assessed the impacts of CC management practices on various main crops grown under different production systems or the potential interactions of agronomic practices (applied to CCs and main crops) with pedo-climatic factors. The previously published CC meta-analyses and reviews identified the learning curve involved in adopting CCs and provided valuable information to improve CC management. Concomitantly, CC research has expanded, and studies with new CC varieties and approaches evaluating CC-induced effects on crop yield and other ecosystem services are continually being published. Consistently with Challinor et al. [25], Marcillo and Miguez [18], and Ponisio et al. [26], this study contributes to building knowledge, improving the robustness of study results, and comparing the results of recent CC research with the previously published meta-analyses.

Herein, the recent literature on CC research (from January 2015 to April 2021) was used to synthesize a quantitative analysis to better understand the crop (main crop and CC) management practices, their interactions with environmental factors, and their effects on subsequent crop yield in temperate climates. The major objectives of the study were (a) to determine the crop yield response with and without CC; and (b) to evaluate the effect of CC management (e.g., CC species type, timing of CC termination, and CC residue incorporation), main crop management (species/type, production system, tillage, and N fertilizer application to main crop), and environmental variables (soil texture and mean annual precipitation) on crop yield response. Quantitative summarization of CC research will identify management and cropping systems that impact crop yield, leading to improved CC recommendations for growers' decision making and potentially enhancing CC adoption in temperate climates.

2. Materials and Methods

2.1. Data Collection

The database for the meta-analysis was prepared by conducting a comprehensive literature search of peer-reviewed articles published from January 2015 to April 2021 using Google Scholar, CAB abstracts, and Web of Science search engines, as well as University of Guelph theses and dissertation collection. The literature was searched by using keywords in the search string "cover crop *or* winter cover crop *or* green manure crop *or* catch crop or intermediate crop *or* service crop *and* crop yield *or* crop productivity". Due to the limited number of CC studies conducted in Europe (only 6 studies), this meta-analysis focused on studies conducted exclusively in North America. To be included in the database and to ensure that the effects on subsequent crop yield were solely due to CC treatments, the following criteria were used: (a) study had a control treatment (no CC or fallow); (b) treatments had at least 3 replicates; (c) study was conducted in the field in a temperate climate, i.e., studies were performed under climate class C based on Koppen–Gieger classification [27] to represent the temperate climate; (d) study was conducted in North America; (e) subsequent crop yield data was reported; (f) study did not include CCs grown as green manure crops for an entire growing season without any main crop; and (g) CCs were planted and terminated prior to planting the main crop. Using the aforementioned criteria, 50 studies published in peer-reviewed journals and 13 unpublished studies (grower reports, theses, and dissertations) were selected for the meta-analysis (Table 1). Data were extracted directly from the tables and text from the published peer-reviewed articles and unpublished studies. Additionally, to extract the data reported in the figures, WebPlot Digitizer (version 4.3) [28] was used.

Table 1. Summary of the articles included in the meta-analysis. ^{z} OSCIA = Ontario Soil and Crop Improvement Association.

	Reference	Year	Main Crop	Cover Crop Type	Study Location	Peer-Reviewed Journal
1	Kaspar and Bakker [29]	2015	Grain corn	Non-legume	Iowa, USA	✓
2	Pantoja et al. [30]	2015	Grain corn and soybean	Non-legume	Iowa, USA	✓
3	Cicek et al. [31]	2015	Spring wheat	Non-legume	Manitoba, Canada	✓
4	Thilakarathna et al. [32]	2015	Grain corn	Legume and non-legume	Ontario, Canada	✓
5	Bulan et al. [33]	2015	Cabbage	Non-legume	Wisconsin, USA	✓
6	Lance Ouellette [34]	2015	Squash	Mixture and non-legume	Ontario, Canada	✗
7	Sara Alford [35]	2015	Grain corn and soybean	Mixture and non-legume	Indiana, USA	✗
8	Welch et al. [36]	2016	Soybean and grain corn	Mixture and non-legume	Illinois, USA	✓
9	Belfry and Van Eerd [37]	2016	Seed corn	Mixture, legume, and non-legume	Ontario, Canada	✓
10	Gieske et al. [38]	2016	Grain corn	Non-legume	Minnesota, USA	✓
11	Mehring et al. [39]	2016	Potato	Mixture, legume, and non-legume	North Dakota, USA	✓
12	Bietila et al. [40]	2016	Pepper, snap bean, and potato	Non-legume	Wisconsin, USA	✓
13	Evans et al. [41]	2016	Dry bean	Non-legume	Manitoba, Canada	✓
14	Ashworth et al. [42]	2016	Grain corn	Legume	Tennessee, USA	✓
15	Seth Appelgate [43]	2016	Grain corn	Mixture and non-legume	Iowa, USA	✗
16	Ryan Haden [44]	2016	Grain corn	Legume and non-legume	Ohio, USA	✗
17	Coombs et al. [45]	2017	Grain corn	Legume	Ontario, Canada	✓
18	Jahanzad et al. [46]	2017	Potato	Legume and non-legume	Massachusetts, USA	✓
19	Chu et al. [47]	2017	Soybean	Mixture and non-legume	Tennessee, USA	✓
20	Belfry et al. [48]	2017	Processing tomato	Mixture and non-legume	Ontario, Canada	✓
21	Thomas et al. [49]	2017	Spring wheat	Non-legume	Alberta, Canada	✓
22	John Hampton Krzton-Presson [50]	2017	Muskmelon	Mixture and non-legume	Iowa, USA	✗
23	Heather Darby [51]	2017	Soybean	Mixture	Vermont, USA	✗
24	Liebman et al. [52]	2018	Grain corn	Legume	North Carolina, USA	✓
25	Chalise et al. [53]	2018	Soybean	Mixture	South Dakota, USA	✓
26	Chahal and Van Eerd [3]	2018	Processing tomato	Non-legume and mixture	Ontario, Canada	✓
27	Cholette et al. [54]	2018	Grain corn	Mixture, legume, and non-legume	Ontario, Canada	✓
28	Van Eerd [4]	2018	Processing sweet corn and fresh bean	Legume and non-legume	Ontario, Canada	✓
29	Nunes et al. [55]	2018	Grain corn	Mixture	New York, USA	✓
30	Jaclyn Clark [56]	2018	Grain corn, soybean, and silage corn	Mixture, legume, and non-legume	Ontario, Canada	✗

Table 1. *Cont.*

	Reference	Year	Main Crop	Cover Crop Type	Study Location	Peer-Reviewed Journal
31	Heather Darby [57]	2018	Sweet corn	Mixture and non-legume	Vermont, USA	✗
32	Hunter et al. [58]	2019	Silage corn	Mixture, legume, and non-legume	Pennsylvania, USA	✓
33	Adeli et al. [59]	2019	Grain corn	Non-legume	Mississippi, USA	✓
34	Larkin [60]	2019	Green bean, sweet pepper, and yellow squash	Mixture and non-legume	Maine, USA	✓
35	Wang et al. [61]	2019	Silage corn	Non-legume	Maryland, USA	✓
36	Kaye et al. [62]	2019	Silage corn	Mixture, legume, and non-legume	Pennsylvania, USA	✓
37	Yang et al. [63]	2019	Grain corn	Legume	Ontario, Canada	✓
38	Flood and Entz [64]	2019	Dry bean	Non-legume	Manitoba, Canada	✓
39	Yang et al. [65]	2019	Soybean and grain corn	Non-legume	Mississippi, USA	✓
40–41	OSCIA ^{z} report [66,67]	2019	Soybean	Non-legume	Ontario, Canada	✗
42	Aaron Patrick Brooker [68]	2019	Grain corn	Mixture, legume, and non-legume	Michigan, USA	✗
43	Cameron Ogilvie [69]	2019	Grain corn	Mixture and non-legume	Ontario, Canada	✗
44	Matthew Stewart [70]	2019	Grain corn	Mixture, legume, and non-legume	Ontario, Canada	✗
45	Luna et al. [71]	2020	Broccoli	Mixture, legume, and non-legume	Oregon, USA	✓
46	Acharya et al. [72]	2020	Soybean	Non-legume	Iowa, USA	✓
47	Adler et al. [73]	2020	Grain corn and soybean	Mixture	Missouri, USA	✓
48	Tobin et al. [74]	2020	Grain corn	Mixture	South Dakota, USA	✓
49	Adeyemi et al. [75]	2020	Grain corn	Non-legume	Illinois, USA	✓
50	Brooker et al. [76]	2020	Grain corn	Legume and non-legume	Michigan, USA	✓
51	Mohammed et al. [77]	2020	Grain corn	Non-legume	Iowa, USA	✓
52	Behnke et al. [78]	2020	Grain corn	Non-legume	Illinois, USA	✓
53	Agomoh et al. [79]	2020	Winter wheat	Legume	Ontario, Canada	✓
54	Andersen et al. [80]	2020	Grain corn	Legume	North Dakota, USA	✓
55	Zhou et al. [81]	2020	Cucumber	Legume and non-legume	Ontario, Canada	✓
56	Wauters et al. [82]	2021	Broccoli	Mixture and non-legume	Minnesota, USA	✓
57	Kandel et al. [83]	2021	Soybean and wheat	Non-legume	South Dakota, USA	✓
58	Hunter et al. [84]	2021	Grain corn	Mixture, legume, and non-legume	Pennsylvania, USA	✓
59	Sigdel et al. [85]	2021	Sugarbeet	Legume and non-legume	Minnesota, USA	✓
60	Rahman et al. [86]	2021	Tomato	Non-legume	West Virginia, USA	✓
61	Hirsh et al. [87]	2021	Grain corn	Non-legume	Mid-Atlantic, USA	✓
62	Langelier et al. [88]	2021	Winter wheat	Legume and non-legume	Quebec, Canada	✓
63	Farzadfar et al. [89]	2021	Root crops, sweet corn, and broccoli	Non-legume	Saskatchewan, Canada	✓

In addition to CC, co-varying factors which might have had a potential effect on crop yield were included in the database. The co-varying factors selected in the meta-analysis were consistent with the previously published meta-analyses and were found to have the greatest influence on the subsequent crop yield [13,17,18]. The factors were broadly categorized into CC management, main crop management, and environment. Cover crop factors consisted of type of CC (legume, grass, nonlegume broadleaf, or a mixture), amount of dry aboveground CC biomass at or near termination (low, $\leq$1 Mg ha^{-1}; medium, >1 and $\leq$3 Mg ha^{-1}; high, >3 and $\leq$5 Mg ha^{-1}; and very high, >5 Mg ha^{-1}), time of CC termination (spring or winter), and CC residue incorporation (yes or no; Table 2). The main aspects of crop management were classified into different categories, such as the type of production system (certified organic field crops, certified organic vegetables, non-organic field crops, or non-organic vegetables), tillage (no-tillage, minimum-tillage, or plow-tillage), type of crop (field or vegetable crops), and N fertilizer inputs to the main crop (yes or no). Field crops were categorized into 5 groups (dry bean (*Phaseolus vulgaris* L.), winter wheat (*Triticum aestivum* L.), silage corn, grain corn, and soybean). The environment variable was classified into soil texture (coarse, medium, or fine [90]) and mean annual precipitation at the study sites (>700 mm, 500 to 700 mm, or <500 mm; Table 2). Cover crop aboveground biomass and precipitation data were classified as categorical variables. As is consistent with previously published reviews on CCs [5,91], aboveground CC biomass was categorized in this study. Similarly to McClelland et al. [92], the lower, middle, and upper ranges of the quartile were used to classify the mean annual precipitation. A description of the variables along with the number of observations in each analysis is provided in Table 2. To enhance the quantitative analysis and to reduce publication bias, the studies reporting the effects of CC in combination with other management factors (e.g., tillage, fertilizer) were considered as separate observations [9,93]. Likewise, if a study was conducted at multiple locations and over different years, data from each year and location were treated as independent observations due to potential differences in weather conditions, soil texture, and crop rotation in different years and locations [94,95].

Table 2. Description of the variables included in the database, total heterogeneity (Q_t), and *p* values to evaluate the impact of soil and crop management factors on the crop yield response ratio. Dependent variable was the natural log of the crop yield response ratio. ^{z} Bold font for *p* values < 0.05 indicates significant heterogeneity or statistical effect in the crop yield response ratio according to the tested variables.

Moderating Variable	Variable Description	Number of Observations	Heterogeneity Analysis		Mixed Model Analysis	
			Q_t	*p* Value	F Value	*p* Value
Cover crop management						
Cover crop type		672	59.1	**<0.0001** ^{z}	9.65	**<0.0001**
	Non legume broadleaf		18.2	0.9485		
	Legume		8.41	**0.0029**		
	Grass		21.4	**0.0005**		
	Mixture		11.1	**0.0041**		
Aboveground cover crop biomass at termination		398	21.3	**<0.0001**	4.87	**0.0024**
	Low		4.83	0.5719		
	Medium		10.3	0.5622		
	High		1.14	0.2293		
	Very high		5.03	**0.0003**		
Time of cover crop termination		661	58.9	**<0.0001**	10.3	**0.0014**
	Winter		3.66	**0.0003**		
	Spring		55.2	0.5077		
Cover crop residue incorporation		536	52.0	**<0.0001**	2.01	0.1569
	Yes		50.8	0.9183		
	No		1.21	0.1562		

Table 2. *Cont.*

Moderating Variable	Variable Description	Number of Observations	Heterogeneity Analysis		Mixed Model Analysis	
			Q_t	*p* Value	F Value	*p* Value
Main crop management						
Crop production system		672	59.1	**<0.0001**	5.37	**0.0012**
	Non-organic field crops		13.1	0.3790		
	Non-organic vegetables		19.9	0.0758		
	Certified organic field crops		8.87	**0.0101**		
	Certified organic vegetables		17.0	**0.0160**		
Type of crops		672	59.1	**<0.0001**	0.63	0.4265
	Vegetables		36.9	0.6490		
	Field		22.0	0.2939		
Tillage		88	15.1	**0.0467**	0.38	0.6836
	Plow		1.29	0.7435		
	Minimum		0.33	0.2825		
	No tillage		13.5	**0.0280**		
N fertilizer input		98	14.1	**<0.0001**	1.07	0.3036
	No		12.8	0.3882		
	Yes		1.25	0.4910		
Environment						
Soil texture		596	52.1	**<0.0001**	6.08	**0.0024**
	Coarse		10.8	**0.0005**		
	Medium		39.4	0.9275		
	Fine		1.91	0.2327		
Mean annual precipitation		551	43.0	**<0.0001**	6.49	**0.0022**
	>700 mm		20.8	**0.0001**		
	500 to 700 mm		1.88	0.5085		
	<500 mm		20.2	0.3467		

2.2. Data Analysis

To evaluate the effect of CCs on the subsequent crop yield, a response ratio (RR) was calculated by dividing the main crop yield with CC treatment by that with no CC control (Equation (1)).

$$RR = \frac{Yield_{\text{cover crop}}}{Yield_{\text{no cover crop}}} \quad (1)$$

Response ratio is a dependent variable and has been widely used to assess the effects of experiment factors [18,96]. The response ratio for each observation was transformed to a natural logarithm scale (ln(RR)) primarily to linearize the metric between numerator and denominator [97]. Additionally, ln(RR) is better suited for meta-analysis than RR due to a more normal distribution of ln(RR) than RR [22,97]. Although ln(RR) values were used for statistical analysis, the values were back-transformed to RR to facilitate the interpretation of the study results [98,99].

To conduct a meta-analysis, treatment means and a measure of variability are generally required to determine the within- and between-study variance [97,100]. However, only 20 out of 63 studies compiled in the present database reported measures of variability. Therefore, to include all the studies in the analysis, an un-weighted meta-analysis using the ln(RR) was conducted in SAS (SAS Institute, version 9.4, Cary, NC, USA) to calculate the bootstrapped (with 9999 iterations) 95% confidence interval (CI) [94,95,98]. If the 95% CI did not overlap 1, the effects of categorical variables on RR were considered significant at $p < 0.05$ [94,98,99]. Furthermore, forest plots demonstrating the mean crop yield RR and

95% CI for the different groups within each moderator variable were prepared in order to analyze the trends in the crop yield response. A response ratio of 1 indicated no difference in crop yield between the CC treatment and the no-CC control.

As described in Han et al. [98] and Tian et al. [101], the total heterogeneity (Q_t) for each group was tested using a Chi-square test to determine whether the effects of variables on effect size were different across studies (Table 2). The total heterogeneity for each group represented the sum of within- (Q_w) and between-group (Q_b) heterogeneity [97]. To further investigate the main and interactive effects of the categorical variables on ln(RR), a mixed-model analysis was conducted using PROC GLIMMIX in SAS, where the moderating variables were the fixed effects while the study was the random effect. Consistently with previous meta-analyses [9,102,103], and to maximize the number of observations used in the statistical analysis, the crop yield response to each variable was analyzed separately. Since CC performance and its effects on subsequent crop yield are largely dependent on the type of CC species, the interaction of CC type with the remaining moderator variables was assessed.

3. Results and Discussion

3.1. Overview of the Studies Included in the Analysis

Our dataset consisted of 672 observations collected from 63 studies conducted in temperate climates exclusively in USA and Canada (Table 1). From the 63 studies we collected, grain corn, soybean, and vegetable crops dominated the dataset (Table 1), with 326, 73, and 193 observations, respectively.

The test for total heterogeneity in the crop yield dataset was significant (Q_t = 59.1, p < 0.0001, n = 672), indicating that the crop yield ln(RR) among the observations was not homogenous. Cover crops either decreased, increased, or had no effect on crop yield ln(RR) in 42%, 51%, and 7%, respectively, of the total observations (data not shown). Therefore, crop yields with CC were either equal to or greater than the control for 58% of the total observations in our dataset. Within the group in which crop yield decreased with CC, crop yield was 15% less than the control (data not shown). Despite the numerous benefits provided by CC, the risk of a loss in crop yield with CC is one of the major challenges deterring CCs' adoption in cropping systems [104]. The exact mechanism through which CC reduces or increases crop yield is highly complex and controlled by several co-varying factors related to both CC and main crop management, as well as the environmental conditions [3,5,9,13,18]. Therefore, in this study, the impact of the aforementioned moderating variables on the crop yield response (i.e., ln(RR)) was investigated.

3.2. Impact of CC Management and Aboveground Biomass on Crop Yield Response

3.2.1. Type of CC

Cover crop types were categorized into legumes, grasses, nonlegume broadleaves, and mixtures to investigate the crop yield RR (Table 2). Of the reviewed studies, leguminous CC species primarily consisted of hairy vetch (*Vicia villosa* L.), red clover (*Trifolium pratense* L.), and field pea (*Pisum sativum* L.). Among the grass CC species reviewed in our dataset (Figure 2), cereal rye (*Secale cereale* L.), annual ryegrass (*Lolium multiflorum* L.), and oat (*Avena sativa* L.) had the greatest frequency. Ruis et al. [91] also reported that grass CCs, such as cereal rye, were the most researched CC species in temperate climates. Brassica had the greatest frequency among the nonlegume broadleaf CC species, whereas grass and legume CC species dominated the dataset for the CC mixtures (Figure 2). The test for heterogeneity (Q_t = 59.1, p < 0.0001, n = 672; Table 2) and mixed model analysis (p < 0.0001) for CC types was significant; hence, the CC type influenced the crop yield RR. Among the CC types tested in our study, legume (RR = 1.11, n = 110) CC species were associated with significantly greater crop yield RR than the no-CC control (Figure 3). The crop yield RR for the remaining CC types (nonlegume broadleaves and mixtures) was greater, but not significantly different, than the no-CC control (Figure 3). For instance, the mean crop yield RR values for the nonlegume broadleaf CC species and mixtures were 1.04 (n = 122) and

1.08 (n = 165), respectively (Figure 3). In contrast, grass CC species had lesser (RR = 0.96, n = 275), but not significantly different, crop yields than the no-CC control (Figure 3). The bootstrapped 95% CI for the grasses, nonlegume broadleaves, and mixtures overlapped with 1, suggesting a similar effect of the CC and no-CC control on the subsequent crop yield (Figure 3).

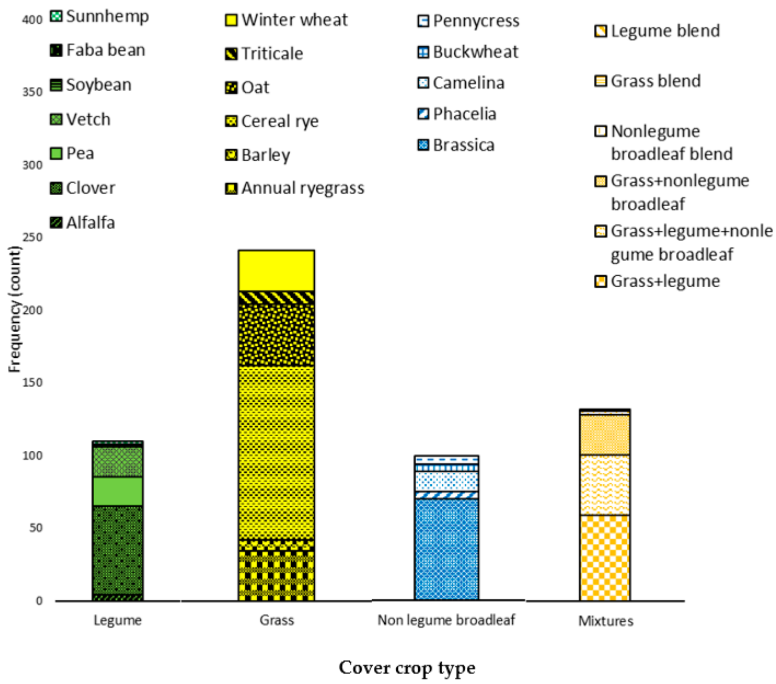

Figure 2. Frequency of legume, grass, and non-legume broadleaf cover crop species, as well as mixtures, which were evaluated in the studies used for the meta-analysis.

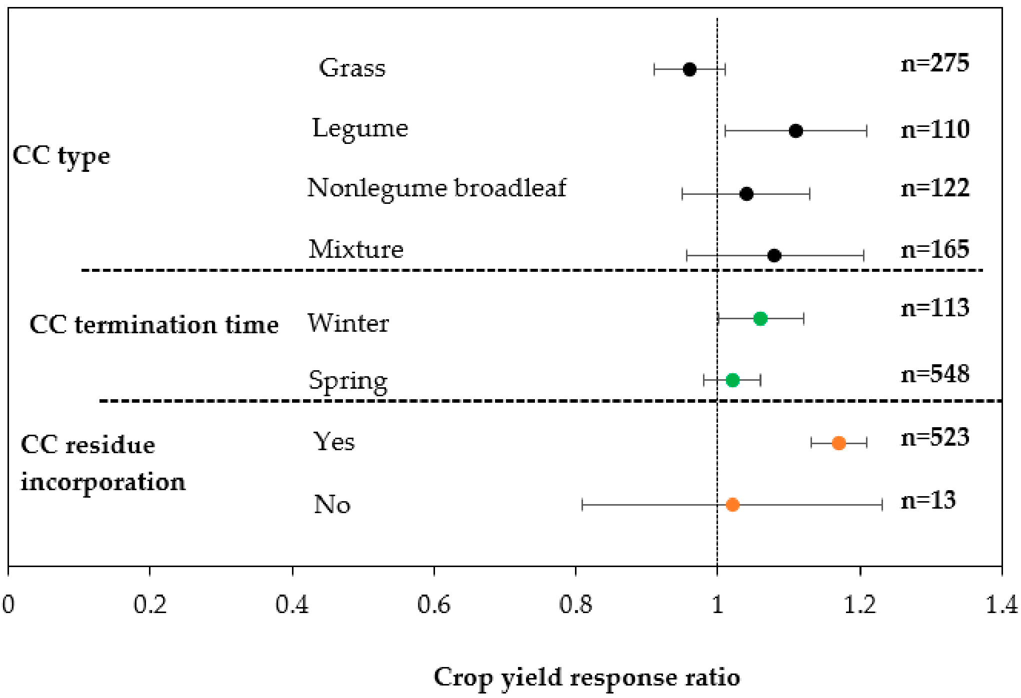

Figure 3. Mean crop yield response ratio (ratio between crop yield with cover crops and the control with no cover crops) and 95% confidence interval for cover crop management factors investigated in the meta-analysis. n represents the number of observations.

Crops following leguminous CC had an 11% greater yield than the no-CC control. As is similar to our findings, Daryanto et al. [9] and Marcillo and Miguez [18] reported an increase in crop yield with leguminous CC, which might be primarily related to increased soil N availability. Legume CC residues undergo rapid mineralization due to narrow C:N (<25:1) at termination; thus, there is an increased potential for N availability to the crops following legume CC in the rotation [62]. In addition, legume CC might provide some non-N benefits, such as increasing soil moisture conservation, weed control, and reducing pest and pathogen infestations [13,18,105], which might have contributed to yield increases following legume CC. Our finding of decreased crop yields with grasses, nonlegume broadleaves, and mixtures compared to leguminous CCs was consistent with previous analyses conducted by Marcillo and Miguez [18], Miguez and Bollero [13], and Daryanto et al. [9]. Grass CCs tend to have wide C:N at termination, which results in N immobilization, a reduction in N supply for the next crop, and a potential decrease in crop yield [106]. Furthermore, the release of allelopathic compounds by cereal rye might negatively impact the main crop yield [107–109]. Despite no gain in crop yield with grass CC, integration of grass CC in crop rotations is beneficial as it increases soil health and soil organic C, while reducing soil mineral N losses [5,7,13,110]. Likewise, our finding of a neutral effect of CC mixtures on subsequent crop yield was consistent with the meta-analysis conducted by Florence and McGuire [15]. In our study, CC mixtures were dominated by grass and legume CC species (Figure 2). As is consistent with our analysis, it has been reported previously that mixing legumes with grass CC mitigated the negative effects of grass CC on crop yield [62,106]; no yield decline with CC mixtures was observed in our analysis (Figure 3). In contrast to our meta-analysis findings, several studies have reported the positive influences of CC mixtures on subsequent crop yield [3,18,47,111]; these were attributed to the high biomass production of CC mixtures, which may be associated with high seeding rates [15,112]. However, the discrepancy in crop yield response following the use of CC mixtures might be related to CC management strategies and the type of CCs grown in the mixtures [113].

3.2.2. Cover Crop Aboveground Biomass at Termination

The amount of aboveground biomass produced by CC largely impacts the subsequent crop yield [5,29,91,114]. In this study, the impact of aboveground biomass produced by CC at or near the time of termination on the subsequent crop yield was evaluated. In our meta-analysis, aboveground CC biomass was reported in 60% of the observations. Despite the positive association between the amount of aboveground CC biomass and ecosystem services (such as nutrient uptake, N availability, erosion control, soil moisture conservation, and weed suppression) provided by CC [5,91], 40% of the observations in our meta-analysis did not report the CC biomass which accumulated in either the fall or spring seasons. Hence, future CC research must consider the quantity of CC biomass produced as a critical factor to accurately discern and make informed decisions regarding the CC-induced effects on crop productivity.

Our analysis revealed that the impacts of aboveground CC biomass on crop yield vary with the type of CC species grown (i.e., highly species-specific). This was confirmed by a significant interaction between the CC type and the CC aboveground biomass at termination ($p = 0.0039$; Table 3). Thus, the effect of amount of aboveground CC biomass on crop yield response was assessed separately for each CC type (grasses, legumes, mixtures, and nonlegume broadleaves) (Figure 4). Our results suggest that within grass CC species, medium (RR = 0.95, n = 89), high (RR = 0.86, n = 14), and very high (RR = 0.81, n = 20) aboveground CC biomass resulted in lesser, yet non-significant, crop yield with CC than the no-CC control (Figure 4), whereas crop yield was statistically greater with CC than the no-CC control when the CC aboveground biomass was low (RR = 1.09, n = 84; Figure 4). Decreases in crop yield in high and very high biomass categories with grass CCs might be related to (a) allelopathic effects of grass CCs (particularly cereal rye) and (b) N immobilization during the spring season, which, perhaps, decreased N availability for the next crop. A similar effect of grass CC species on crop yield was reported in the meta-analysis by Marcillo and Miguez [18]. Unlike grass CCs, legume CCs led to significantly greater crop yield compared to the no-CC control in the groups with the medium (RR = 1.16, n = 27; Figure 4) and high (RR = 1.14, n = 5) amounts of CC aboveground biomass. Legume CCs have greater potential to supply N to the next crop than grasses and nonlegume broadleaves; hence, increases in the leguminous CC biomass increased the CC aboveground N content, which perhaps contributed to a yield increase in the next crop. The crop yields between the CC groups and the no-CC control were not statistically different in the aboveground biomass categories using mixtures and nonlegume broadleaf species (Figure 4), suggesting the need for more research to further elucidate the interactive effects between CC aboveground biomass and species type on crop yield. There were very few observations in the high (n = 3) and very high (n = 3) biomass categories with nonlegume broadleaf CC species (Figure 4), which limited the ability of this study to derive conclusions related to crop yield.

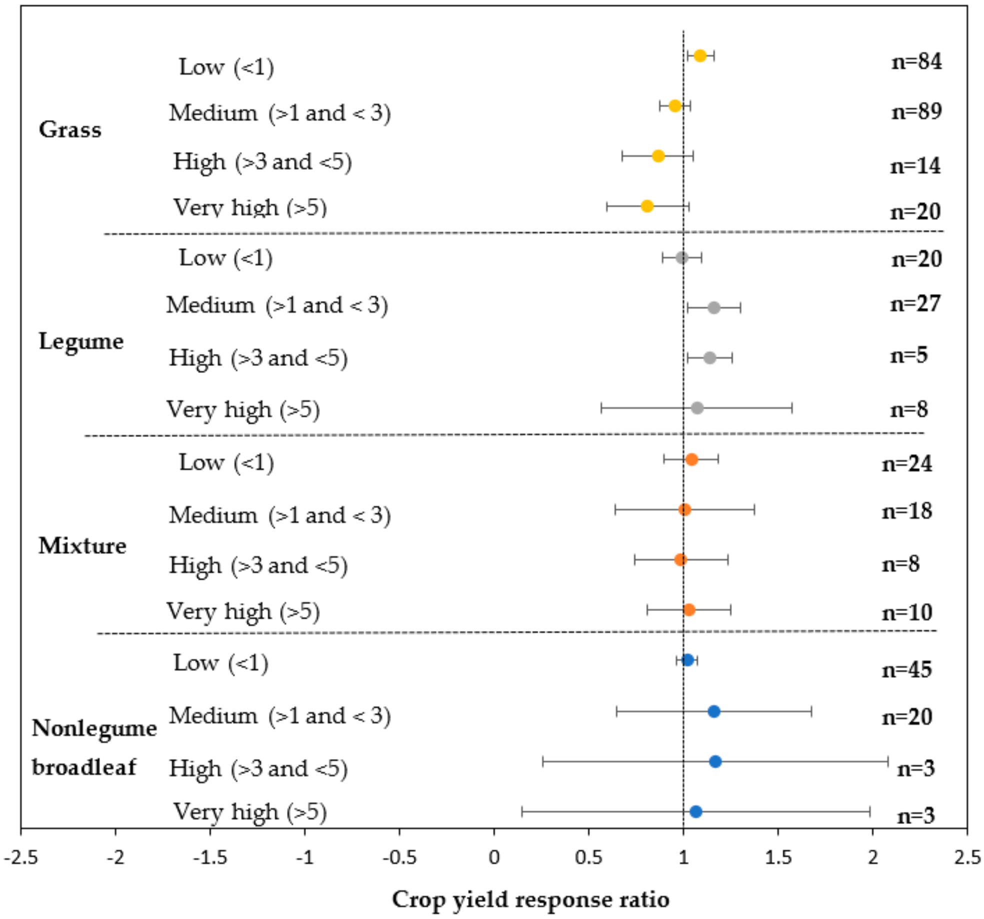

Figure 4. Mean crop yield response ratio (ratio between crop yield with cover crops and the control with no cover crops) and 95% confidence interval for the interaction between cover crop type and cover crop aboveground biomass investigated in the meta-analysis. n represents the number of observations.

Table 3. Mixed model analysis for test of significance of two-way interactions between cover crop type and moderating variables and their effects on crop yield response ratio. Dependent variable was natural log of crop yield response ratio. [z] Bold font for p values < 0.05 indicates significant statistical interaction in crop yield response ratio due to the tested variables.

Moderating Variable	*Pr > F*
CC type x CC aboveground biomass	**0.0039** [z]
CC type x time of CC termination	0.8114
CC type x CC residue incorporation	0.5073
CC type x crop production system	**<0.0001**
CC type x type of crop	**0.0061**
CC type x tillage	0.1067
CC type x N fertilizer inputs	0.0759
CC type x soil texture	**0.0037**
CC type x mean annual precipitation	**0.0123**

The test for heterogeneity (Q_t = 21.3, p < 0.0001, n = 398) and the mixed model analysis (p = 0.0024; Table 2) for CC aboveground biomass were significant, suggesting that subsequent crop yield varied among the CC aboveground biomass sub-groups. Despite the significant heterogeneity in the dataset, the mean crop yield among the CC aboveground biomass categories (low (RR = 1.01, n = 173), medium (RR = 1.02, n = 154), high (RR = 0.96, n = 30), and very high (RR = 0.87, n = 41)) was not significantly different between the CC groups and the no-CC control (Figure S1). Unlike the positive effects of increasing CC biomass on crop yield, which have been derived from several studies [5,18,114], our results demonstrated that the effects of the amount of CC aboveground biomass on crop yield are complex and depend on the type of CC grown. The complex effect of the amount of CC biomass produced on crop productivity was further confirmed by the large crop yield variability and lower crop yield RR with CCs compared to the no-CC control in high and very high biomass categories, suggesting a potential risk to crop yield with an increase in the amount of aboveground CC biomass.

3.2.3. Cover Crop Termination Time

The test for heterogeneity (Q_t = 58.9, p < 0.0001, n = 661; Table 2) and mixed model analysis (p = 0.0014; Table 2) were significant for CC termination timing, suggesting that CC termination timing impacted the crop yield response. Consequently, crop yield RR between the categories of winter and spring termination of CC was analyzed. The forest plot in Figure 3 shows the effect of CC termination timing on crop yield RR. The bootstrapped 95% CI of the winter and spring (usually in May) termination timing group overlapped by 1; thus, suggested that crop yield following winter (RR = 1.06, n = 113) and spring (RR = 1.02, n = 548) termination of CC was not different between the CC groups and the no-CC control (Figure 3). Between both CC termination groups, winter CC termination led to a 48% greater variability than spring termination, mainly due to fewer observations in the winter termination group (Figure 3). One potential reason for the low crop yield response when CCs were terminated in spring might be associated with the allelopathic effects of rye [107,108]. Numerous studies have confirmed that the allelopathic effects of cereal rye on the main crop are more pronounced when cereal rye is terminated late, closer to main crop planting than winter termination [30,109,115,116]. Unlike our study, Marcillo and Miguez [18] reported a high crop yield when CCs were terminated in spring, closer to main crop planting. Likewise, Wortman et al. [113,117] reported a greater corn yield with CCs which were terminated late in the spring, primarily because of increased CC biomass production and early-season weed suppression. As is consistent with our results, a meta-analysis by Daryanto et al. [9] reported that winter termination of CC might increase crop yield in dry, temperate climates, mainly due to conservation of soil moisture for the next main crop. A study by Rosa et al. [118] in temperate climates found that spring termination of CC stimulated N immobilization and reduced corn yield. Growing CC for an extended period in dry temperate climatic conditions is not a promising approach for obtaining major crop yield benefits, mainly due to excessive water consumption by the CC species.

Although there was no significant interaction between CC type and termination time in our study (Table 3), the duration of the CC growing season largely impacts the aboveground biomass produced; a long CC growing season results in high CC biomass accumulation [91,114]. Furthermore, the termination timing of CC (winter vs. spring) is largely a function of the CC species, as some CC species are winter-hardy while some are winter-killed. The majority of the compiled studies in our analysis consisted of winter-hardy CCs, such as cereal rye and hairy vetch (Figure 2), which was evident as there were a greater number of observations within the spring termination group (n = 548) than the winter group (n = 113). Cover crop species such as oat and radish (*Raphanus sativus* L.) are winter-killed, whereas CCs such as cereal rye and red clover can overwinter and, therefore, can be terminated in winter or spring. At spring sampling, winter-killed CC species will be dead and somewhat decomposed, and, hence, would have less biomass remaining than the winter-hardy species. Moreover, winter-killed CC species might accumulate less biomass than winter-hardy species due to their shorter growing seasons. Similarly to the CC type, the termination timing of CCs has direct implications on the quantity and quality of CC residue [18,119], which is the major pathway for CC-induced effects on subsequent crop yield. Therefore, CC management is a crucial factor for enhancing the main crop yield.

3.2.4. Cover Crop Residue Incorporation

The test for heterogeneity (Q_t = 52.0, $p < 0.0001$, n = 536; Table 2) for CC residue incorporation was significant; thus, the crop yield RR values from two sub-groups (i.e., CC residues incorporated into soil or not) were further investigated. The mean crop yield following incorporation of CC residues into soil was greater than 1 (RR = 1.17, n = 523). The bootstrapped 95% CI for the sub-group did not overlap with 1, suggesting that the incorporation of CC residues into the soil increased crop yield with CCs compared to the no-CC control (Figure 3). It is possible that incorporating CC residues might have increased soil microbial activity, soil aeration, and nutrient availability for the next crop [101], which may have increased crop yield. It was also reported that the potential negative effects of rye allelopathy on the main crop yield were significantly reduced with the incorporation of CC residues, perhaps due to rapid decomposition of the residue by soil microbes upon incorporation [109]. Additionally, a meta-analysis by Basche et al. [102] reported that incorporating CC residues into soil during the spring season in temperate climates might increase the availability of C-rich substrates for microbial growth and, depending on the amount of decomposition, may increase the potential for N loss in the environment, which may have a negative impact on the subsequent crop yield. Likewise, meta-analyses by Daryanto et al. [9] and Zuber and Villamil [103] highlighted that the incorporation of CC residues into soil with tillage might disturb the soil microenvironment and negatively impact the fungal colonization, microbial biomass, and crop yield.

Unlike CC residue incorporation, leaving the CC residues on the soil surface increased crop yield (RR = 1.02, n = 13), but the crop yield was not significantly different between the CC group and the no-CC control (Figure 3). Several studies have reported inconsistent crop yield effects when CC residues are left on the soil surface [9,110,120]. Additionally, as it relates to CC residue incorporation (n = 523), there were very few observations in which CC residues were left on the soil surface (n = 13). The low number of observations resulted in a very high variability in crop yield when CC residues were not incorporated into the soil. In agreement with the literature, results from this study suggest the need for future research to better elucidate strategies to manage CC residues, such as precision incorporation.

3.3. Impact of Main Crop Management on Crop Yield Response to Cover Crops

3.3.1. Type of Production System and Main Crop Type

In our analysis, a significant interaction ($p < 0.0001$; Table 3) between the CC type and the crop production system was observed, suggesting that the crop yield response to CC depended on the type of CC grown under different production systems. Our results suggested that the crop yields with grass (RR = 1.14, n = 51) and leguminous (RR = 1.19, n = 23) CC species were greater than the no-CC control with the use of non-organic vegetable production systems (Figure 5). However, grass CC species decreased the crop yield with non-organic field crops, certified organic field crops, and certified organic vegetable crops (Figure 5). Nonlegume broadleaf and mixture CCs had no effect on crop yield under any of the tested production systems (Figure 5). Mixtures and nonlegume broadleaves in certified organic field crops and legume CCs in certified organic vegetable production systems led to very large variability in crop yields, mainly due to a lack of observations. Relative to non-organic field crops, non-organic vegetable production systems showed either significantly greater or similar crop yields with CCs compared to the no-CC control, thus confirming the better suitability of CC species for vegetables than for field crop production systems in temperate climates. When the crop yield data were pooled across CC types, the results suggested that CC usage in non-organic vegetable systems significantly increased the subsequent crop yield (RR = 1.12, n = 125; Figure S2). However, no yield increase with CC was observed in certified organic vegetable production systems (RR = 0.96, n = 80; Figure S2). Similarly, studies by Chahal and Van Eerd [7], Brennan [121], and Buchanan et al. [122] found yield benefits with CCs in non-organic vegetables.

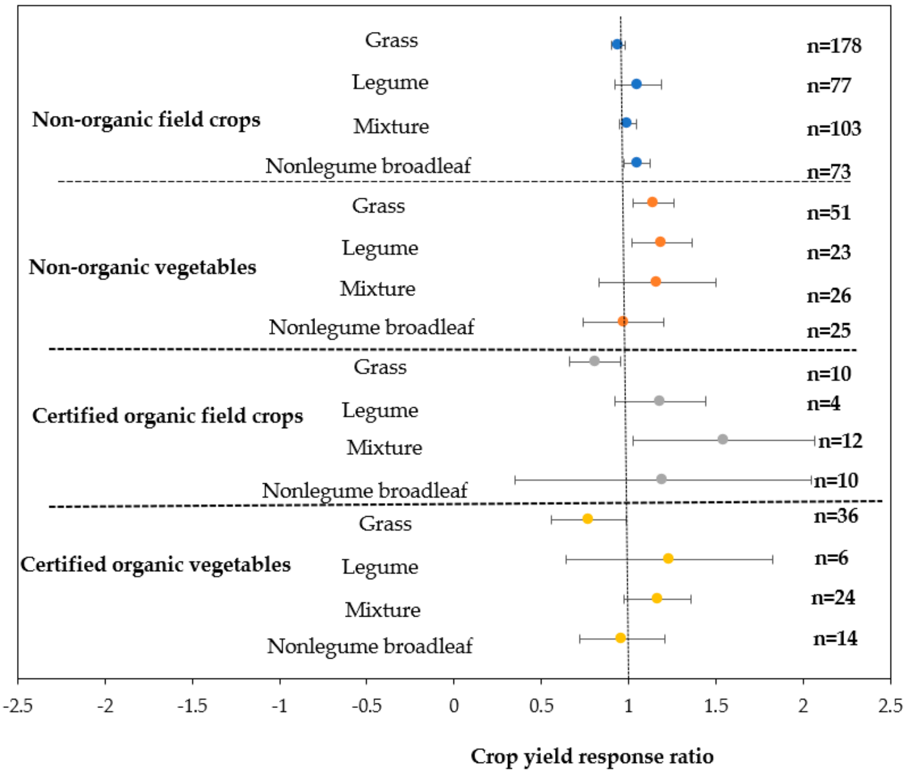

Figure 5. Mean crop yield response ratio (ratio between crop yield with cover crops and the control with no cover crops) and 95% confidence interval for the interaction between cover crop type and production system investigated in the meta-analysis. n represents the number of observations.

Furthermore, a significant interaction between the type of main crop and CC ($p = 0.0061$; Table 3) revealed that there were no yield penalties with CC in vegetable crops (Figure 6), whereas grass CCs in field crops significantly decreased the crop yield (Figure 6). Cover crops significantly increased the yield (RR = 1.06, n = 193) of vegetable crops (Solanaceae, Brassicaceae, Fabaceae, Gramineae, and Cucurbitaceae; Figure S2). As is consistent with our findings, several studies have reported yield enhancements in vegetable crops following CCs [3,4,48,123–125]. Relative to field crops, vegetables have a shorter growing season. For instance, in temperate climates, vegetable crops are usually harvested in late August to early September. This allows for timely planting and good establishment, growth, and aboveground biomass accumulation of CC, which contribute to positive effects on soil health and following crop yield. Among the field crops, grain corn (RR = 1.03, n = 326), soybean (RR = 1.06, n = 109), and winter wheat (RR = 1.01, n = 23) showed greater, yet non-significant, crop yields with CCs than the no-CC control (Figure S2). In contrast, dry bean (RR = 0.94, n = 16) and silage corn (RR = 0.90, n = 41) had lesser crop yields with CCs than the no-CC control (Figure S2). Furthermore, on average, grain corn yield was 14% greater than that of silage corn in our study. Similar results related to a decrease in silage corn yield following CC were reported in a meta-analysis by Marcillo and Miguez [18]. The potential causes of silage corn yield loss are not exclusively attributed to CCs, but might be related to an extensive removal of crop residue from silage corn fields, an increased potential for erosion, and a loss of nitrate from soil [18]. Less crop yield response to CC in field crop systems represents a major challenge for CC adoption by these growers in temperate climates; hence, further research is needed that focuses on CC management in field crop systems.

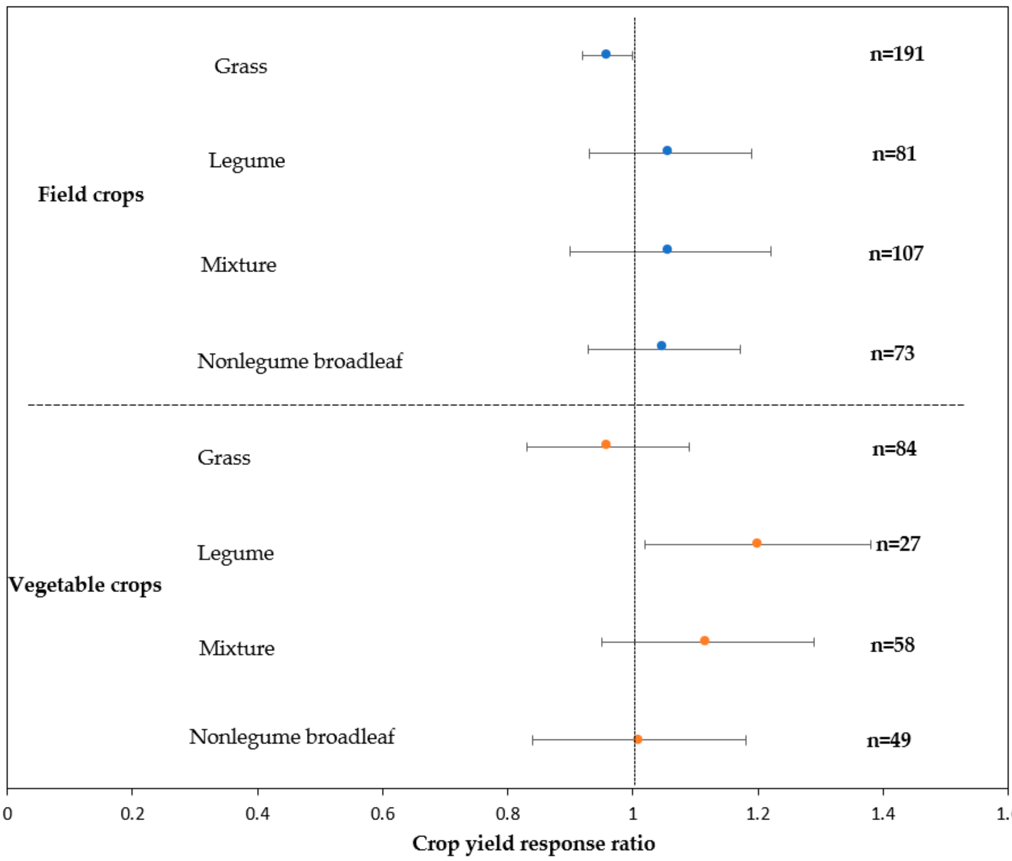

Figure 6. Mean crop yield response ratio (ratio between crop yield with cover crops and the control with no cover crops) and 95% confidence interval for the interaction between cover crop type and type of main crop investigated in the meta-analysis. n represents the number of observations.

3.3.2. Type of Tillage System

Tillage is another agronomic management variable which impacts the CC-induced effects on subsequent crop yield. Therefore, the crop yield response to CCs was evaluated under three types of tillage system (no-tillage, minimum tillage, and plow). The test of heterogeneity (Q_t = 15.1, p = 0.0467, n = 88) for tillage systems was significant; thus, the sub-groups (no-tillage, minimum tillage, and plow) were further investigated. The crop yield was significantly greater with CC than the no-CC control for the no-tillage (RR = 1.21, n = 67) and plow tillage systems (RR = 1.1, n = 13; Figure 7). In contrast, the crop yield with CC under minimum tillage (RR = 0.94, n = 8; Figure 7) was lesser, yet non-significant, compared to the no-CC control. Relative to minimum and plow tillage, CCs increased crop yield in no-tillage systems. The crop yield from CC adoption in the no-tillage system was 28% greater than in the minimum tillage group and 10% greater than in the plow tillage group. As is consistent with our results, several studies and meta-analyses have reported the positive effects of no-tillage on soil properties, soil microbial activities, soil structure, and organic matter stabilization [103,126,127]. No-tillage combined with CCs, therefore, has positive implications for subsequent crop yield. Our result of a greater crop yield with no-tillage than with plow tillage in addition to CCs was in agreement with Marcillo and Miguez [18] and Mitchell et al. [128]. The significant variability in crop yield with no-tillage systems indicated that (a) the management of crop residues and main crop seeding, as well as their establishment to increase crop yield, in no-tillage systems are complex; and (b) there were differences in agronomic management (type of CC and main crop species, time of CC termination) in the evaluated studies. Several studies have reported negative effects of no-tillage on crop yield in temperate climates [129–132], primarily due to excessive soil moisture at the time of planting, resulting in water-logging, poor crop establishment [133], and the immobilization of nutrients [129,130]. Despite the inconsistent effects of no-tillage on crop yield which were observed in the literature, our results suggest that the combination of no-tillage with CCs improves crop yield and might be more consistent in improving soil [126] and crop [128] characteristics than no-tillage alone.

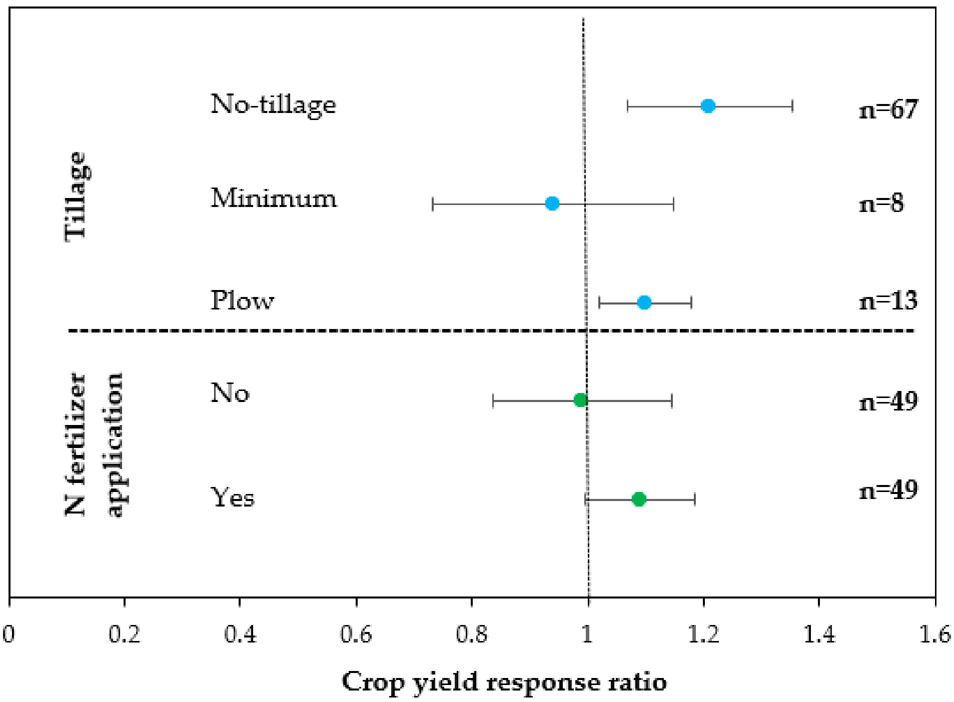

Figure 7. Mean crop yield response ratio (ratio between crop yield with cover crops and the control with no cover crops) and 95% confidence interval for main crop management factors (tillage and N fertilizer application) investigated in the meta-analysis. n represents the number of observations used for calculating the response ratio.

In our study, the large crop yield variability under minimum tillage was attributed to a smaller number of observations than no-tillage (Figure 7). Our result of high crop yield with CC under plow tillage contrasted with previous studies [128]. For instance, a meta-analysis by Zuber and Villamil [103] found a decline in soil microbial properties with conventional tillage. Similarly, meta-analyses by Norris and Congreves [21] and Roper et al. [134] found an increase in soil total N and soil respiration with minimum tillage than with conventional tillage; hence, plow tillage negatively impacted the subsequent crop yield. Considering these previous findings, it is possible that the negative effects of plow tillage on soil and crop attributes might have been alleviated by integrating CC in crop rotations. That is, the positive impacts of plow tillage on crop yield observed in this study might be related to the interactive effects of tillage and CCs. Another possible explanation is that soil organic matter mineralization is stimulated under plow tillage, which might release and increase N supply for the subsequent crops and increase crop yield.

3.3.3. Fertilizer N Inputs to Main Crops

The application of fertilizers, especially synthetic N fertilizers, to main crops is a common practice and critical factor for sustaining crop yield. Therefore, CCs' effects on the main crop yield with and without the application of synthetic N fertilizers were evaluated. The test of heterogeneity for N inputs was significant (Q_t = 14.1, $p < 0.0001$, n = 98; Table 2), confirming the need to assess the effects of sub-groups on crop yield. Although not significantly different between the CC groups and the no-CC control, crop yield was greater with N inputs (RR = 1.09, n = 49; Figure 7), but decreased when no N fertilizer inputs were applied to the main crop (RR = 0.99, n = 49; Figure 7). In comparison to that without N fertilizer application, the crop yield following CC was 10% greater with N. Crop yield variability without N fertilizer application was larger than with N fertilizer (Figure 7). As is consistent with our findings, Tonnito et al. [14] reported no significant differences in crop yield following CC with and without the application of N fertilizer to the main crop. Moreover, our result of no differences in crop yield following CC between N fertility treatments suggests that CC did not decrease the crop yield in the absence of N fertilizer inputs, indicating system resiliency with N management. Although not significant, a trend ($p < 0.10$) was observed for the interaction between CC type and N fertilizer input (Table 3). Overall, the results suggest that the use of CCs may provide an opportunity to reduce the N fertilizer application to the main crop. Therefore, CC adoption might be an effective option for maintaining soil N supply and availability to the main crop, especially in low-input agriculture, where agronomic management strategies focusing on reducing the application of N fertilizers are desirable [9,14,18].

3.4. Impact of Environmental Variables on Crop Yield Response to Cover Crops

3.4.1. Soil Texture

The results of the mixed model analysis suggested a significant interaction ($p = 0.0037$; Table 3) between CC type and soil texture, suggesting that the effect of CC species on crop yield depended on the soil texture. All tested CC types had either increased or similar crop yields as the no-CC control with coarse textured soil (Figure 8). Likewise, when the effects of the soil texture on crop yield were pooled across the CC types, crop yield with CC was significantly greater than the no-CC control in coarse textured soils (RR = 1.08, n = 192; Figure S3). However, no significant differences in crop yield between the CC groups and the no-CC control were observed for medium and fine textured soils (Figure S3). Fine textured soils have high water-holding capacity and cation exchange capacity [103], which might have positive implications on soil microbial activity, nutrient availability, and subsequent crop yield; however, our results suggest that the adoption of CCs in fine textured soils does not benefit the subsequent crop. Coarse textured soils, on the other hand, resulted in better CC growth and establishment than medium and fine textured soils, mainly due to good aeration, soil structure, and less clay content [103]. Unlike medium and fine textured soils, coarse textured soils did not decrease crop yield with grass CC, suggesting that coarse textured soils helped to mitigate the negative effects of grass CC on the main crop yield. Legumes significantly increased crop yield compared to the no-CC control with coarse (RR = 1.18, n = 46) and medium (RR = 1.045, n = 54; Figure 8) textured soil. The negative effects of poor aeration, high clay content, and the delayed drying during the spring season associated with fine textured soils on the main crop yield were not observed for the legumes and mixtures (which primarily consisted of grass and legumes) in this study; thus, legume CCs' effects on the main crop yield led to a high resilience to variation in soil conditions. However, legume and mixture CC species led to significant variability in crop yield under fine textured soils due to a lack of observations. Based on our study results, further research is required to investigate the processes related to CCs' performance and its effects on crop yield in various soil textural classes, particularly fine-textured soils.

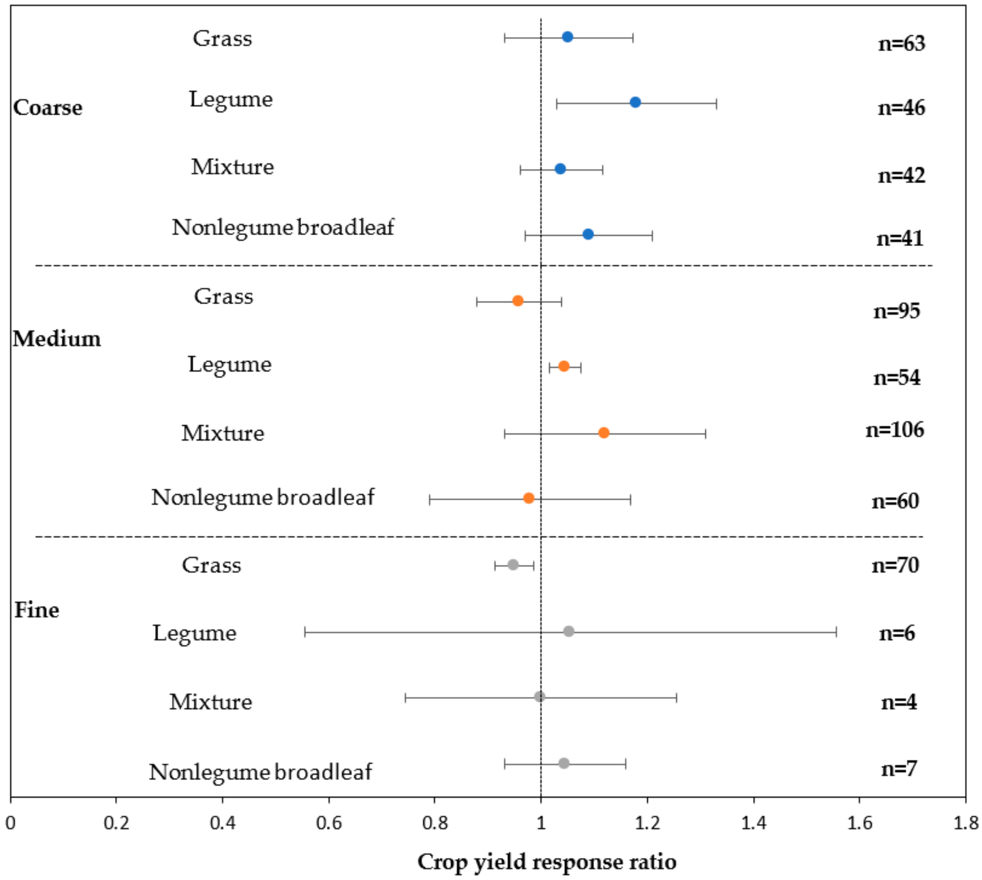

Figure 8. Mean crop yield response ratio (ratio between crop yield with cover crops and the control with no cover crops) and 95% confidence interval for the interaction between cover crop type and soil texture investigated in the meta-analysis. n represents the number of observations.

3.4.2. Mean Annual Precipitation

Our results demonstrated that the crop yield response to CCs under varying precipitation conditions was dependent on the CC type (legume vs. non-legume CCs), as confirmed by a significant interaction between precipitation and CC type ($p = 0.0123$; Table 3). For instance, with >700 mm precipitation, legume CCs led to a significantly greater crop yield than the no-CC control (Figure 9). It is possible that with >700 mm precipitation conditions, legume CC biomass increased, which increased the N content of aboveground CC biomass, the N availability to the next crop, and the next crop yield. In contrast with our results, a meta-analysis by Basche et al. [102] reported that CCs, under high precipitation conditions, increase the loss of N in the environment during the spring season, depending on the amount of decomposition, and may result in a reduction in N availability to the next crop, and, thus, might have negative implications for the subsequent crop yield.

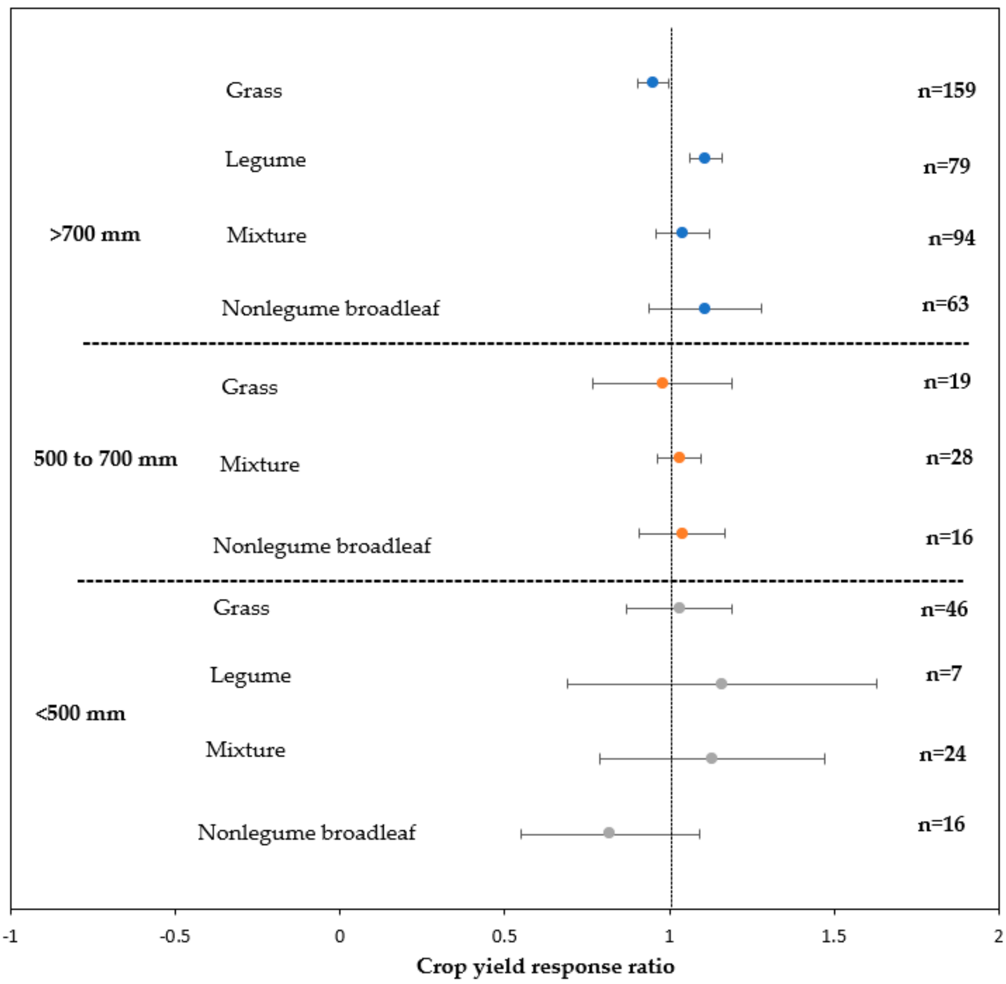

Figure 9. Mean crop yield response ratio (ratio between crop yield with cover crops and the control with no cover crops) and 95% confidence interval for the interaction between cover crop type and mean annual precipitation investigated in the meta-analysis. n represents the number of observations. Impact of legume cover crops under the 500 to 700 mm precipitation condition was not evaluated due to the low number of observations.

Grasses, on the other hand, led to lesser crop yields than the no-CC control in all precipitation conditions (Figure 9). Relative to legumes, grass CC species compete more with the main crop for soil water, mainly due to the rapid root growth and high root biomass of grass CCs [5,23]. Therefore, grasses contributed to a decrease in crop yield even under high precipitation conditions (>700 mm; Figure 9). Crop yield with non-legume broadleaf CCs and mixtures was not different than that with the no-CC control under all tested precipitation conditions. It is possible that in mixes, grasses outperformed the legume CCs in terms of growth and biomass production when precipitation conditions were >700 mm and 500 to 700 mm; thus, crop yield differences were not observed (Figure 9). Further investigation is, therefore, required to discern the mechanisms responsible for differences in crop yield with different CC types under variable precipitation conditions.

The test for homogeneity (Qt = 43.0, $p < 0.0001$, n = 551) and mixed model analysis ($p = 0.0022$; Table 2) were significant; consequently, the sub-groups were assessed in order to understand the CC-induced effects on crop yield. Our results suggest that the crop yield was significantly greater in the CC group than in the no-CC control group when the mean annual precipitation was >700 mm (RR = 1.06, n = 395; Figure S3). With >700 mm of annual precipitation, there would be fewer issues related to competition for soil water between CCs and the main crop. Adequate rainfall conditions favor CCs' growth and biomass accumulation, and, thus, contribute to increasing the subsequent crop yield. A decline in crop yield was observed with CC when the mean annual precipitation fell into the categories of 500 to 700 mm (RR = 0.99, n = 63) and <500 mm (RR = 0.98, n = 93; Figure S3). As is consistent with our results, studies by Blanco-Canqui et al. [5], Daryanto et al. [9], and Rusinamhodzi et al. [135] found that CC-induced effects on subsequent crop yield decreased with a decrease in total precipitation. Cover crops uptake water from the soil, which may result in loss of soil moisture via transpiration during the CC growing season [14,136]. Therefore, the use of CCs is not considered to be a promising agronomic management strategy in dry temperate climates.

4. Conclusions

Our meta-analysis compiled recent data on crop yields following CC application from 63 recent studies conducted in temperate climates, and evaluated the effects of ten moderator variables on the main crop yield. The results of our meta-analysis revealed that the interactions of different CC types with pedo-climatic variables and management factors are important to better understand the CC-induced effects on subsequent crop yield. These interactive effects also confirm the need to focus research efforts on CC types to optimize crop productivity. Our results suggest that the crop yield following the use of legume and mixture CCs was either greater than or equal to that of the no-CC control under the conditions of fine textured soil and low precipitation. The mixture CCs evaluated in this study consisted primarily of legumes and grasses. It is possible that the benefits of legume CCs masked the negative effects of grass CCs on crop yield under conditions that limited the CCs' performance. The crop yield did not decrease with the use of legume CCs under fine textured soil and low precipitation conditions, suggesting that the effects of legume CCs were more resilient to changes in pedo-climatic conditions than the remaining CC types tested in this study. Even though the crop yield was not significantly larger than that of the no-CC control for three (field crops, CC aboveground biomass, and N fertilizer application) out of ten moderator variables, the crop yield RR > 1 suggests a net benefit of including CCs in crop rotations, and supports the hypothesis that the integration of CCs in cropping systems is an effective approach for maintaining agroecosystem productivity. Our study results identified opportunities for further research to optimize management, which might improve the adoption of CCs in production systems. Although one would expect greater effects of CCs on crop attributes to be observed in the long term ($\geq$10 years), the majority (70%) of the available studies compiled in our database were not long-term. Therefore, more research on CCs in the long term is needed to comprehensively assess the main crop yield benefits of CCs and to better reflect farmers' commitment to CC use.

Additional research evaluating the economic returns from CCs in various production systems is needed. Although crop yield response following CCs is a major parameter determining the adoption of CCs within a cropping system, future research elucidating the benefits of CCs on soil attributes such as soil microbial activity and diversity, nutrient cycling, and soil C and N storage, which might be valuable for increasing the adoption of CCs in agricultural systems.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su15086517/s1. Figure S1. Mean crop yield response ratio (ratio between crop yield following cover crops and no cover crop control) and 95% confidence interval for the cover crop aboveground biomass investigated in the meta-analysis. n represents the number of observations. Figure S2. Mean crop yield response ratio (ratio between crop yield following cover crops and no cover crop control) and 95% confidence interval for main crop management factors investigated in the meta-analysis. n represents the number of observations used for calculating the response ratio. Figure S3. Mean crop yield response ratio (ratio between crop yield following cover crops and no cover crop control) and 95% confidence interval for soil texture and mean annual precipitation investigated in the meta-analysis. n represents the number of observations used for calculating the response ratio.

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Abbreviations

CC = cover crops; ln(RR) = natural log of response ratio; no-CC = no cover crop; RR = response ratio.

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