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A Meta-Analysis Approach to Estimate the Effect of Cover Crops on the Grain Yield of Succeeding Cereal Crops within European Cropping Systems

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Abstract: Farming practices such as cover cropping, crop rotation systems, and soil tillage practices, along with climate conditions and soil type play important roles in determining final crop production. Numerous empirical studies have documented the heterogeneous effects of cover crops on the yield of successive crops, exhibiting variations across diverse regions, climate regimes, soil characteristics, cover crop types, and agricultural management practices. A meta-analysis was conducted to comprehensively summarize and evaluate the impact of cover crops (CCs) in the agroecosystem. The main goal of the study is to promote a transition towards more sustainable cereal crop production by exploring the potential of currently unexploited CCs in Europe. The study demonstrated that the incorporation of legume CCs resulted in the most pronounced and statistically significant increase in grain yield among cereal crops. CCs from the *Brassicaceae* family also demonstrated a positive impact on grain yield under southern European climates. Cover cropping had a positive effect on the subsequent cash crop under conventional tillage practice. A positive, but not significant impact, was detected under both conservation tillage practices, which include reduced tillage (RT) and no-till (NT). The result of the study suggests that NT practices are more suitable for Northern Europe, while RT practices are preferable for Southern Europe zones. This study indicates that the adoption of cover cropping represents a viable and effective agronomic strategy for enhancing grain yield in cereal crops cultivated across European agricultural systems.

Keywords: sustainable farming practices; cereal grain crop; agro-ecological service crops; climatic conditions; soil tillage

1. Introduction

Cover cropping could be considered an age-old practice adopted by farmers based on the cultivation of a single or a mixture of well-defined species. Cover crops (CCs) are planted during the bare period between two cash crops with the primary objective of covering the soil to protect it from adverse external effects, thereby supporting multiple ecosystem services [1–3]. While CCs have been historically regarded as an age-old practice for managing agroecosystems, their incorporation into modern cropping systems is gradually emerging as a promising ecological intensification strategy. They significantly contribute to sustainable agriculture as reported by the European Green Deal for the achievement of the 2030 goals [4]. The main aim of cover cropping is to develop a climate-smart agricultural technique based on the integration of improved and sustainable rural livelihoods to ensure long-lasting benefits to the agroecosystems worldwide. Indeed, CCs contribute organic matter to the soil in the form of living or residual biomass, and provide positive impacts as reported in several previous studies; for example, they enhanced soil health and fertility [5,6], reduced soil erosion and runoff [6–8], increased soil water infiltration and retention [9,10], improved soil biological diversity [11] and provided habitat for beneficial insects and other wildlife [12–15]. Furthermore, they enhanced crop productivity and stability [16], as well as increased carbon sequestration [17].

Moreover, CCs are an essential component of sustainable farming practices that can lead to decreased input costs. Indeed, cover crops may reduce the need for synthetic fertilizers and pesticides [18,19], reduce nutrient loss, especially nitrogen [20], reduce the energy required for crop production [21], suppress weeds [6,22,23], and mitigate greenhouse gas emissions [1,24]. In addition, it was observed that under cover cropping management, the soil organic matter content is increasing, thereby supporting beneficial microbial activity [25], and consequently affecting nutrient availability [26,27], and improving soil structure [28]. The increased carbon content transforms the soil into a carbon sink, thereby contributing to the reduction of carbon dioxide emissions, one of the main greenhouse gases. Therefore, the cultivation of CCs is proven to be a valuable tool for meeting the needs of carbon farming initiatives [29,30]. All these benefits represent specific functional outcomes to develop resilient agroecosystems able to sustain the main crop yield while preserving soil from climate change and extreme weather events such as flooding, drought, and variations in precipitation quantities and patterns.

Several factors should be carefully considered when adopting cover cropping in farm management practices. Cover crop termination, for example, represents a key aspect that may affect their benefits to the agroecosystem [31]. CCs are commonly killed before sowing or transplanting the following crop to avoid undesired competition effects. Under conventional tillage systems, cover crop residue is mown and incorporated with a plough or disc. This termination method allows rapid decomposition and nutrient release, benefiting the following cash crop. However, the high nutrient release may exceed the initial nutrient demand of the seedling during its early growth stages, leading to an elevated risk of nutrient loss into the environment. On the other hand, the adoption of conservation tillage practices such as reduced tillage (RT) and no-tillage (NT) aims to provide a minimum soil disturbance to increase the decomposition of previous crop residues. Conservation tillage combined with continuous soil cover using the previous crop residues and suitable crop rotation represent the backbone of conservation agriculture [32]. Currently, a wide range of studies have demonstrated that the adoption of conservation agricultural strategies provides numerous advantages to agroecosystems [33–35], even if their benefits varied depending on the agro-environmental conditions of a specific site and the adopted strategy.

Currently, many farmers worldwide are not completely convinced to adopt and convert their farms to conservation agriculture systems, despite the different advantages that could be obtained. Indeed, the main challenges and barriers to the adoption of conservation agriculture are represented by a lack of adequate knowledge and skills to implement alternative sustainable approaches [36]. Moreover, different challenges of conservation agriculture adoption could be raised, for example, the permanent soil cover represents a challenge under actual farm situations as residues may be used for livestock feed or considered by farmers as an obstacle for sowing and the establishment of the following seed crop.

Wheat (*Triticum aestivum* L.), maize (*Zea mays* L.), barley (*Hordeum vulgare.* L) and oat (*Avena sativa* L.) represent the main important grain cereal crops in Europe for providing human and animal diets and energy. The grain yield of these cereal crops has been tripled in recent past decades to satisfy the market needs [37] as a result of improved germplasm and intensive management practices such as increased inputs of fertilizer, water and agrochemicals. To achieve an elevated grain yield without causing environmental concerns, it is necessary to follow sustainable management of all production factors in time and space. Although the implementation of cropping systems with the inclusion of cover crops is feasible as it provides several benefits and profits for farmers, their adoption is linked to different challenges that have slowed down their spread in the agroecosystem. There are variable and contrasting results in the literature regarding the effect of cover crops on the grain yield of the main crop. Replacing bare fallow with cover crops could determine negative [38], neutral [39], and positive [40] effects on the consequent cash crop yields [41]. Furthermore, the impact of cover crops on the subsequent crop yield has been reported to vary across regions [42–44], climate conditions [40], soil properties [40,43,44], type of cover crop [43], and farming management practices [40,43,44]. In fact, on one hand, there are studies that reported the importance of cover crops to supply a wide range of ecosystem services that resulted in a great response of the following cash crop in terms of yield and its quality, even if these data are subjected to many discrepancies and inconsistent results, especially when cover crops are tested under those areas that are characterized by climate variability, i.e., dryland areas. Thus, these agro-environmental aspects should be taken into account when starting to approach to cover cropping practice and the complexity of cover crop management in terms of services and disservices should be carefully considered to reduce the negative impact of the cover crop and optimizing the ecosystem services and cash crop response. These contrasting results regarding how cover crops affect the grain production of cereal crops determine the need for a comprehensive quantitative review. To study the impacts of cover crops on cereal grain yield, the adoption of meta-analysis based on validated data from different field studies geographically distributed has multiple advantages compared to site-specific studies. Therefore, a meta-analysis can provide a better description and stronger evidence [45] of the impact of CCs' presence in the agroecosystem. Additionally, this analysis offers an opportunity to explore under which farming practices, climate, and soil conditions, cover cropping systems could lead to improvements in terms of grain yield production. Although up to date, there are a lot of studies that try to address the effect of cover crops in agroecosystems, the available information is difficult to generalize due to the variability and fragility of different agro-climatic conditions; therefore, this meta-analysis is realized with the aim of covering the gap related to the impacts of cover crop adoption on various cereal grain crops grown under different production systems and pedo-climatic conditions based on the more recent evidence reported in the bibliography. The main goal of the current study is to encourage a transition towards more sustainable cereal crop production with currently unexploited cover crops in Europe.

2. Methodology

2.1. Literature Search and Inclusion Criteria

A literature search was conducted to investigate the effect of adopting cover cropping practice on cereals' grain yield in the agroecosystem of European countries. Scopus databases were searched over the last four years for scientific articles published in the English language. We searched the following: TITLE-ABS-KEY ("cover crops") AND (LIMIT-TO-(PUBYEAR, 2019)) OR (LIMIT-TO-(PUBYEAR, 2020)) OR (LIMIT-TO-(PUBYEAR, 2021)) OR (LIMIT-TO-(PUBYEAR, 2022)). The search for articles studied the effects of cover crops vs. fallow bare soils, on the subsequent cereal grain yield carried out in field experiments in Europe.

The identified publications were screened for relevance. A total of 2291 papers were assembled, and their abstracts were screened (Figure 1). The following strict following criteria were applied for the selection of the publications:

(1) Studies reported the effect of cover crop inclusion or bare soil (fallow), on the subsequent cereal grain production;
(2) Only field experiments;
(3) Only in Europe;
(4) Using three or more replicates per treatment;

(5) The comparisons between treatments were conducted at the same location, climate conditions, and received the same farming management.

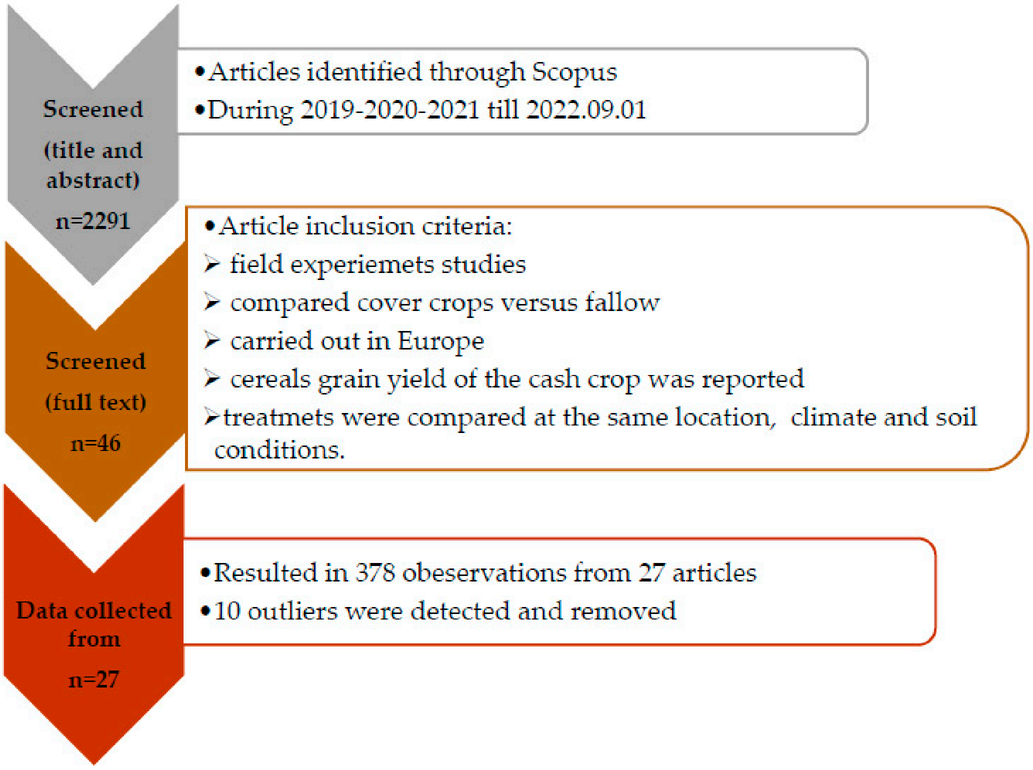

Figure 1. Description of article search and screening process.

After applying these criteria, the total number of 388 independent observations was derived from 27 articles that are presented in Table 1. These observations were from studies conducted in 14 countries in Europe. Data were directly extracted from tables and figures using the software GetData Graph Digitizer (version 2.22) (http://getdata-graph-digitizer.com/, accessed on 16 December 2021). For each study, the following variables were collected: (1) Research site coordinates. (2) Soil tillage practice (tillage practices were classified into three categories: conventional tillage "CT", reduced tillage "RT", and no-tillage "NT"). RT is considered to be any tillage practice lower than the conventional practice. (3) Cropping system as crop a monocropping or crop rotation system (a rotation system was defined by two or more crops grown in sequence in the same field over time). (4) Irrigation practices were divided into rainfed or irrigation management. (5) Soil classification based on the Natural Resources Conservation Service Soils USDA (https://www.usda.gov/, accessed on 23 July 2022) using the reported percentage of sand, silt, and clay. Three different categories were reported based on soil texture data: (i) fine (clay, clay loam, silty clay, silty clay loam), (ii) medium (loam, sandy clay, sandy silt loam, silt loam), or (iii) coarse (loamy sand, sandy clay loam, sandy loam). (6) The European environment was classified into two classes, northern and southern Europe according to [46]. (7) Cover crop genera were classified according to cover crop family (*Boraginaceae*, *Brassicaceae*, *Leguminosae*, *Poaceae*, and *Multigenera* "mixture of two or more families"). (8) Multiple observations of the cash crop grain yield with (CC) and without CC (fallow or bare soils) were obtained from the text, tables or extracted from graphics using the freeware Plot Digitizer (http://getdata-graph-digitizer.com/, accessed on 16 December 2021). If a publication reported results from distinct sites and each had its properties, such sites were kept separate in the analysis. In this study, a database representing studies from 14 countries in Europe (Figure 2) for 6 cereal crops, barley, maize, oat, rice, rye, and wheat, were evaluated under 11 different soil textures. Maize was the most studied crop species and sandy loam was the most represented soil texture.

Table 1. Detailed information on the studies is included in the meta-analysis. Studies are reported in temporal order.

ID	Authors	Year	Country	Crop
[47]	De Notaris et al.	2019	Denmark	Wheat, Oat
[48]	Toom et al.	2019	Estonia	Barley
[49]	Tosti et al.	2019	Italy	Wheat
[50]	Crotty et al.	2019	UK	Oat
[51]	Fontaine et al.	2020	Denmark	Barley
[52]	Salonen and Ketoja	2020	Finland	Barley
[53]	Boselli et al.	2020	Italy	Maize, Wheat
[54]	Alonso-Ayuso et al.	2020	Spain	Maize
[55]	Wittwer et al.	2020	Switzerland	Maize
[56]	Moitzi et al.	2021	Austria	Maize
[57]	Pedersen et al.	2021	Denmark	Barley
[58]	Jensen et al.	2021	Denmark	Barley
[59]	Bonnet et al.	2021	France	Wheat
[60]	Karyoti et al.	2021	Greece	Maize
[61]	Severini et al.	2021	Italy	Maize
[62]	Maris et al.	2021	Italy	Maize
[63]	Fogliatto et al.	2021	Italy	Rice
[64]	Adeux et al.	2021	Italy	Maize, Wheat
[65]	Boulet et al.	2021	Portugal	Maize
[66]	Perdigao et al.	2021	Portugal	Maize
[67]	Dragicevic et al.	2021	Serbia	Maize
[68]	Rodriguez et al.	2021	Sweden	Oat
[69]	Holland et al.	2021	UK	Barley
[31]	Alletto et al.	2022	France	Maize
[70]	Fiorini et al.	2022	Italy	Maize
[71]	Bogužas et al.	2022	Lithuania	Rye
[72]	Cottney et al.	2022	UK	Barley

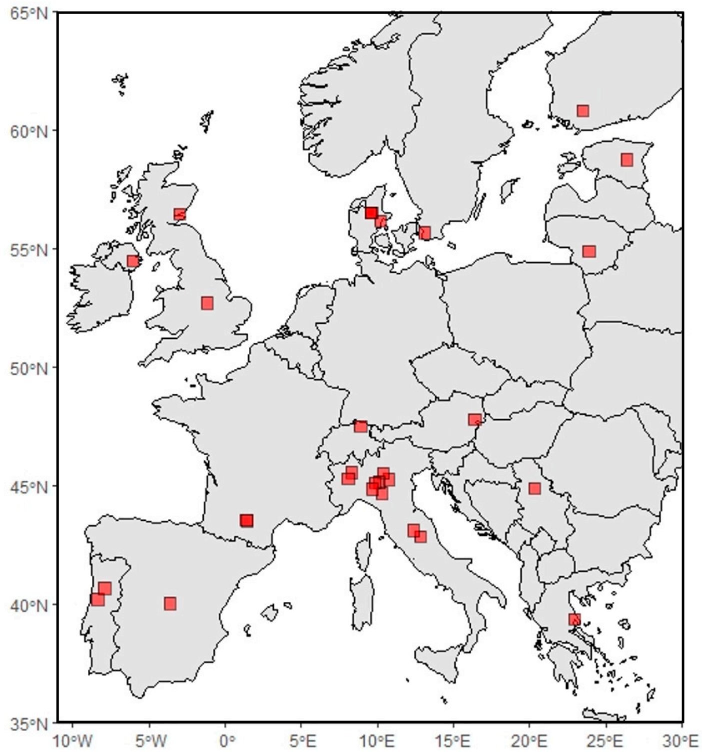

Figure 2. Map of experiment locations included in the analysis. Red squares refer to locations where collected studies were conducted.

2.2. Data Analysis

In this study, the response ratio was used as effect size defined as cereal grain yield following cover crops (CCs) relative to grain yield after no cover crop (NC). Twenty-seven peer-reviewed articles including 388 observations of cover crop effects on cereals' grain yield were analysed. Crop-yield-paired observations under different farming management and environmental conditions in Europe were collected. The standard deviation (SD) was estimated as 0.1 times the mean for studies that did not report SD [73]. The analysis was conducted using a multilevel random-effects model, with studies nested within publications. The response ratios (RR) for each with cover crops (CCs) versus without cover crops (NC) for crop grain yield were calculated as follows:

$$RR = ln\frac{X_{CC}}{X_{NC}}$$

where X_{CC} is the crop yield average for the experimental group CC, and X_{NC} is the crop yield mean for the control group NC. According to Hedges et al. [74], the response ratio is an important and suitable index for meta-analysis in many ecological experiments. This index has the advantage of providing statistical confidence statements (confidence intervals) for the summary of effects across experiments. It also provides a quantification of between-experiment variation that may be useful in the interpretation of the results. The statistical analysis was performed using the natural logarithm of the effect size RR (*ln* RR), which was calculated for each observation/study [74]. The variance of the response ratio v_i was calculated using the equation

$$v_i = \frac{SD^2{}_{CC}}{X^2_{CC}N_{CC}} + \frac{SD^2{}_{NC}}{X^2_{NC}N_{NC}}$$

where the standard deviation is SD_{CC}, the sample size (number of replicates) is N_{CC} for the experimental group, and the standard deviation and the sample size of the outcome in the control group are SD_{NC} and N_{NC}, respectively. In addition, we examined potential outliers (Figure 3) based on a plot of influence diagnostics outliers [75].

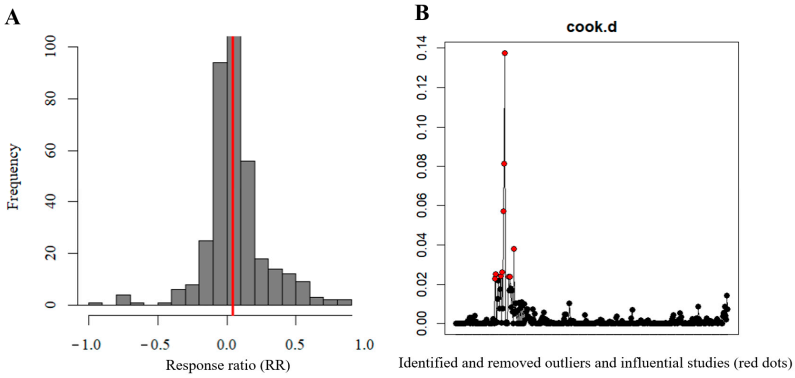

Figure 3. (**A**). Histogram of the effect size represented by the response ratio "RR". (**B**) Influence and outlier analyses using the Cook's distances "cook.d" which provides a test statistic for examining multivariate outliers (red dots).

Effect sizes within the meta-analysis were weighted (w) using the inverse of the variance (v_i) of each study (i) computed as per Hedges et al. (1999) [74]:

$$w = \frac{1}{v_i}$$

Eventually, the weighted mean effect size $\overline{\ln R}$ was estimated as

$$\overline{\ln R} = \frac{\sum(\ln\ RR \times w_i)}{\sum w_i}$$

The 95% confidence interval (CI) was calculated for the mean effect size:

$$95\%\ CI = \overline{\ln R} \pm 1.96\ SE_{\overline{\ln R}}$$

where $SE_{\overline{\ln R}}$ is the standard error of $\overline{\ln R}$ and is computed as

$$SE_{\overline{\ln R}} = \sqrt{\frac{1}{\sum w_i}}$$

The percent change in selected variables was computed using the equation

$$(e^{\overline{\ln R}} - 1) \times 100\ \%$$

The analysis was conducted using a multilevel random-effects model, with studies nested within publications, leading to a multilevel data structure. Using a multilevel model allows for the consideration of additional random effects to account for dependent effect sizes within or across studies. A forest plot [76] was used to summarize the effects on grain yield. Subgroup analyses were conducted to assess the impact of crop species, climate conditions, and soil type on yield response. The meta-analysis was performed using the restricted maximum likelihood estimator (REML) estimation in the RMA.mv model, together with scale functions of the 'metafor' package [77]. The impact of potential outliers and/or influential studies was tested using influential case diagnostics according to [75]. All analyses were performed using the R statistical software language.

3. Results and Discussion

3.1. Cover Crop Botanical Family

The results from a random-effects model indicated that the inclusion of overall observations related to the adoption of cover crop species had a significant positive effect (about 6.5%, n = 378 observations) on cereal grain yield in comparison with bare soils (Figure 4). These results are in agreement with those of Bourgeois et al. [78] who reported a significant positive impact of cover crop inclusion in comparison with bare soil on cereal grain yield. Similarly, Fan et al. [40] concluded the same significant positive impact of CCs instead of fallow overall observations. Furthermore, overall, in 113 meta-analysis assessments, Young et al. [79] indicated a significant positive effect of cover cropping compared to fallow on crop productivity [80].

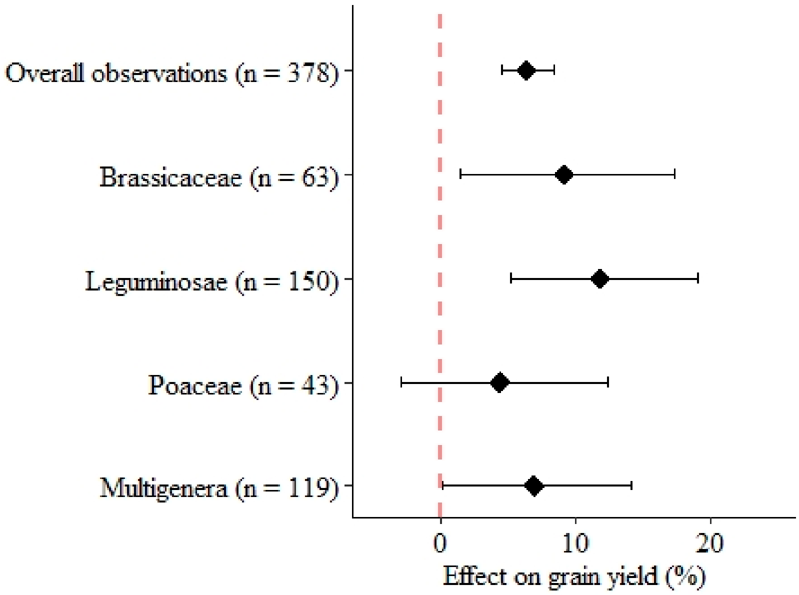

Figure 4. Forest plot for the crop yield response to cover cropping vs. bare fallow soil (CC vs. NC) overall observations and for different cash crop family species, expressed as the average effect size on crop yield (%). Numbers (n) in the parentheses are the number of observations for each subgroup. The vertical line represents the null hypothesis (ln (RR) = 0). The points (♦) represent an estimate of effect size, and the horizontal lines are the associated 95% confidence intervals for the cover crop effect on grain yield.

Cereal crop yield responses to cover cropping in comparison with the bare fallow soil (CC vs. NC) based on the different cover crop botanical family are reported in Figure 4. The response of cereal yields to CCs strongly varied among the cover crop botanical species. According to this study, CCs belonging to *Leguminosae* and *Multigenera* (mixture) are the most studied CC categories in Europe. The majority of mixture categories included legume CCs in their composition. Grain yield production was about 12% higher with CCs belonging to the *Leguminosae* family, compared to those without CCs. Marcello et al. [44] reported that legume CCs led to higher corn yield, while there was no impact for grass CCs. Geng et al. [80] reported that legume cover crops have a significantly beneficial impact to increase the yield of subsequent wheat crops. The highest grain yield responses of cereal crops to legume CCs are associated with increased N content in CC biomass and point to the influence of CCs on N release as a key factor to promote cereal productivity. It is well known that legume CCs fix atmospheric nitrogen (N) and make it available to the subsequent cash crop after the mineralization process [81]. In addition, the accumulated residues of legume CCs are characterized by a lower C/N ratio that leads to a rapid N release available for the following cash crop, allowing for a reduced level of competition for necessary plant nutrients. CCs' C/N ratios can determine net mineralization or immobilization as ratios > 25 to 30:1 and limit plant available nitrogen due to microbial immobilisation. Legume cover crop species are known to impact N availability for up to 8 weeks following termination [82]. While non-legume species had a lower N concentration, legume CCs were able to maintain their concentration independently from the soil N availability, due to N fixation [83]. However, several studies showed as the soil N dynamic is strongly related not only to the botanical species but also to other several aspects that significantly contribute to N mineralization such as the termination method and time, weather conditions and soil characteristics [3,11,17,29,39]. Moreover, legumes are considered an essential choice for soil health management [84]. It has been reported that cover crops such as hairy vetch enhanced soil structure and water-holding capacity [85]. Similarly, following *Brassicaceae* and *Multigenera* (mixture of two or more families) CCs, cereal grain yields were significantly increased on average by 9% (n = 63 observations) and 7% (n = 119 observations, not significant) compared with bare soils, respectively (Figure **4**). Although N fixation may represent an important characteristic of legume cover crops for adding N in the agroecosystems, *Brassicaceae* and other botanical species could positively affect the N dynamic, especially in the presence of a well-expanded root system. Indeed, the root systems of some cover crop species can catch residual nitrogen in the soil which is not used by the previous crop and immobilize it at the root level, while releasing it using the decomposition process for the following cash crop. Elhakeem et al. [86] reported that residues from CCs belonging to *Brassicaceae* compared to fallow provided higher mineral N for the subsequent crop. Additionally, Holland et al. [69] explained increasing grain yield with brassica CCs due to their ability to reduce N leaching. The ability to immobilize the residual soil N other than support the reduction of N fertilizer for the following main crop also represents an environmental benefit able to reduce the pollution effect of some intensive fertilization practices. In addition, *Brassicaceae* CCs provide other ecosystem services such as enhancing soil water capacity, improving soil quality, and suppressing weed infestation [87]. Moreover, Snapp et al. [88] specified that brassica CCs should be considered a valuable option, particularly for pest control. It is also reported that these cover crops led to higher cash crop yield in comparison with fallow due to improved soil characteristics. Furthermore, several previous reports indicated that a mixture of cover crops provides several agronomical and environmental benefits [89–92]. However, it is also interesting to note that the adoption of multiple species of CCs has not provided significant benefits in comparison with well-adapted single cover-crop species. These results are in agreement with [93], even if their impact tended to be positive. This behaviour could be associated with the variability of the pedo-climatic conditions that may affect each species differently with each cover crop mixture causing a variable biomass composition.

Moreover, the results showed no significant differences in cereal crop yield when using cover crops from the *Poaceae* family compared with bare soils. Grass CCs are well known for their ability to improve soil structure due to their root systems, which result in less-compacted soils. In addition, the biomass produced by the grass species has a high C/N ratio that generally led to an immobilization of the residual N and also mineral N applied by fertilizers to the following cash crop, which may reduce its potential yield. A lower percentage of the N released from the cereal rye residue could be stimulated due to the high C/N which could increase the N immobilization when the maize plant is in high need of N [94]. Although the results showed no negative effect on the yield of the following crops compared with the fallow management, the adoption of grass cover crops for cereal grain crops should be carefully weighted by the farmers to avoid the risk of yield loss and the requirement to add additional N fertilizer to balance crop needs. To mitigate these penalties to the following cash crop, it is necessary to consider the time and method of suppression as younger plants have a lower content of lignin and easily mineralize, and in under-conservation agriculture practice, the N immobilization effect is lower than when using cover crops. In addition to its very high C/N ratio (25.4), compared to other shoots, other typical factors had favoured the N immobilization of cereal rye such as lignin, polyphenols, proteins, and soluble carbohydrates and could explain differences in C and N mineralization among the cover crops [95]. Soluble polyphenols slow the mineralization of residue N by forming complexes with proteins, thus making them inaccessible to microorganisms [96]. However, grass cover crops are well known to support several ecosystem services, such as the improvement of organic soil matter, the reduction of N leaching during the fallow period and the possibility to release allelopathic substances both during root growth and also during root decomposition after their suppression.

3.2. Climate Conditions

The response of cereal crop yield to cover cropping practice compared with bare soil subjected to different climate conditions is presented in Figure 5A. The climate conditions were divided into two categories: the Northern and Southern classes of Europe as reported by [46]. The Northern class represents 60% of Europe while the Southern class represents 30%. However, the introduction of CCs seemed to be recommended in Northern Europe in comparison with Southern Europe, probably due to the increasing drought conditions [97]. This can be observed by a higher number of studies conducted in Northern than in Southern Europe. However, the results showed that cover cropping practice compared to fallow was significantly better under Southern Europe conditions in terms of grain yield (+12%, n = 228 observations). Our results confirmed those of Valkama et al. (2015) [98] who demonstrated in a meta-analysis that the amount of annual precipitation did not change the effect of cover crops on grain yield in Nordic Countries (Denmark, Sweden, Finland and Norway). A positive but not significant impact of CC (+6%, n = 150 observations) was detected under Northern European conditions matching no-cover-cropping yields overall.

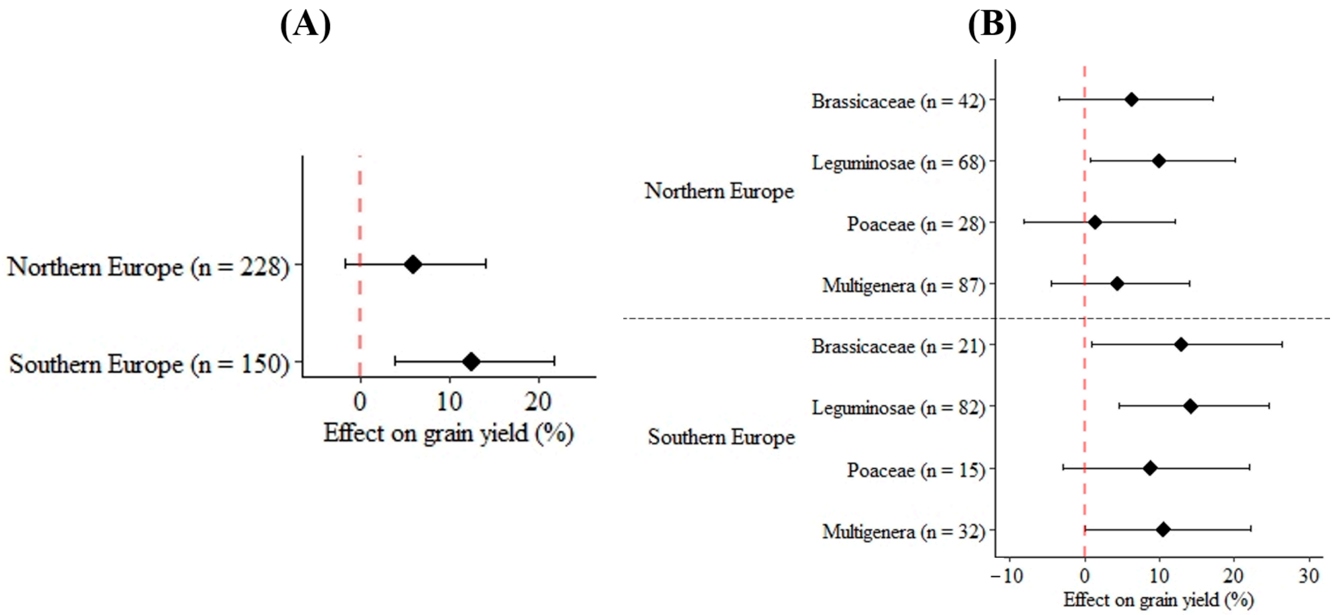

Figure 5. Forest plot for the crop yield response to cover cropping vs. bare fallow soil (CC vs. NC) (**A**) under different European climate conditions, and (**B**) for the interaction between cash crop family species and climate conditions, expressed as the average effect size on crop yield (%). Numbers (n) in the parentheses are the number of observations for each subgroup. The vertical line represents the null hypothesis (ln (RR) = 0). The points (⧫) represent an estimate of effect size, and the horizontal lines are the associated 95% confidence intervals for the cover crop effect on grain yield.

Most of the regions in Southern Europe are characterized by a typical Mediterranean climate with warm winters and dry summers, while Northern Europe is often characterized by humid cold climates. The climatic conditions of the Southern environments may support the establishment and growth of cover crop species that accumulate in time higher biomass compared to Northern environments, thus determining a more intense positive ecosystem service. Under the Mediterranean climate, the higher temperatures compared to the northern area allow for an intensive soil microorganism activity that determines a rapid biomass decomposition and a high level of soil mineral N for the following cereal grain crop, regardless of the cover crop species adopted. Less grain yield in Northern than Southern Europe can be partially explained by higher nitrogen leaching due to the high precipitation in Northern European climates [99]. It should be mentioned that around 67% of the studies that were conducted in Southern Europe received irrigation for the main spring–summer crop.

3.3. Cover Crop Family Species under Different Climate Conditions

The response of cereal crop yield to cover cropping practice in comparison with bare soil management based on the interaction between cover crop botanical family and climate conditions is presented in Figure 5B. According to this study, mixture cover crops are the most studied CC categories in Northern Europe, while *Leguminosae* are the most studied in Southern Europe. It is important to include legumes in the cropping system as they fix nitrogen and affect its availability for the following main cereal crop. As expected, grain yield production was significantly higher with *Leguminosae* CCs compared to fallow in both Northern and Southern Europe (+10% (n = 68 observations) and +14% (n = 82 observations), respectively). However, only in Southern Europe, cover crops belonging to the *Brassicaceae* family significantly increased crop production (+13%, n = 21 observations). Both *Poaceae* and *Multigenera* (mixture) tended to have a higher but not significant grain yield in Southern European (+9 (n = 15 observations) and +11% (n = 32 observations), respectively) compared with Northern European conditions (+1 (n = 28 observations) and +5% (n = 87 observations), respectively). Cover crops are chosen for their agroecological functions that can be provided under specific climatic conditions. Cover crops could provide Biological Nitrogen Fixation (BNF), weed or pest suppression, or prevention of soil erosion. CCs increase the functional diversity and environmental suitability of cropping systems [100].

3.4. Soil Properties

Yield response to cover cropping practice vs. fallow under different soil textures and soil types is reported in Figure 6A,B. Overall, there was a positive trend on all soil texture classifications, even if it was not significant. Contrarily, negative but not significant impacts were noticed under clay loam, sandy clay, and silty clay soils. The significant positive impact was observed only under loamy sand (+14%, n = 21 observations), sandy loam (+12%, n = 122 observations), and silty clay loam (+23%, n = 37 observations) soils.

Moreover, there was a positive trend under all soil type classifications. Significant yield benefit under cover cropping was identified in fine (+12%, n = 68 observations) and coarse (+12%, n = 179 observations) soils. However, crop yields under cover cropping in medium soils were not significantly different from yields under fallow. Young et al. [79] evaluated 113 meta-analysis studies that assessed the impact of several sustainable agricultural management crops, soil, and environmental indicators [79]. In agreement with the results of this study, they stated that crop yields in diverse cropping systems were lower for medium soils compared to fine- and coarse-textured soils.

3.5. Tillage Practice

The crop yield response to CCs instead of fallow was evaluated under three types of tillage practices (plough, reduced tillage, and no-tillage) (Figure 7A). CCs increased grain yield under all tillage practices included in the study. Conservation tillage practices along with cover cropping represent the two main aspects that define conservation agriculture. Li and colleagues [100] showed that conservation tillage practices showed positive effects on the soil's physical properties compared with the conventional tillage practice (CT), a significant impact (about 10% higher, n = 213 observations) on grain yield was only observed under conventional tillage practice (CT). These differences were expected as conservation tillage practices had lower mineralization rates than conventionally tilled soils. Garba et al. [101] reported a decline in cash crop yield and soil mineral nitrogen with cover cropping under both conservation tillage practices (RT and NT) when compared with CT [101]. Moreover, conventional tillage practice helped to control weeds with false-seed-bed techniques [102].

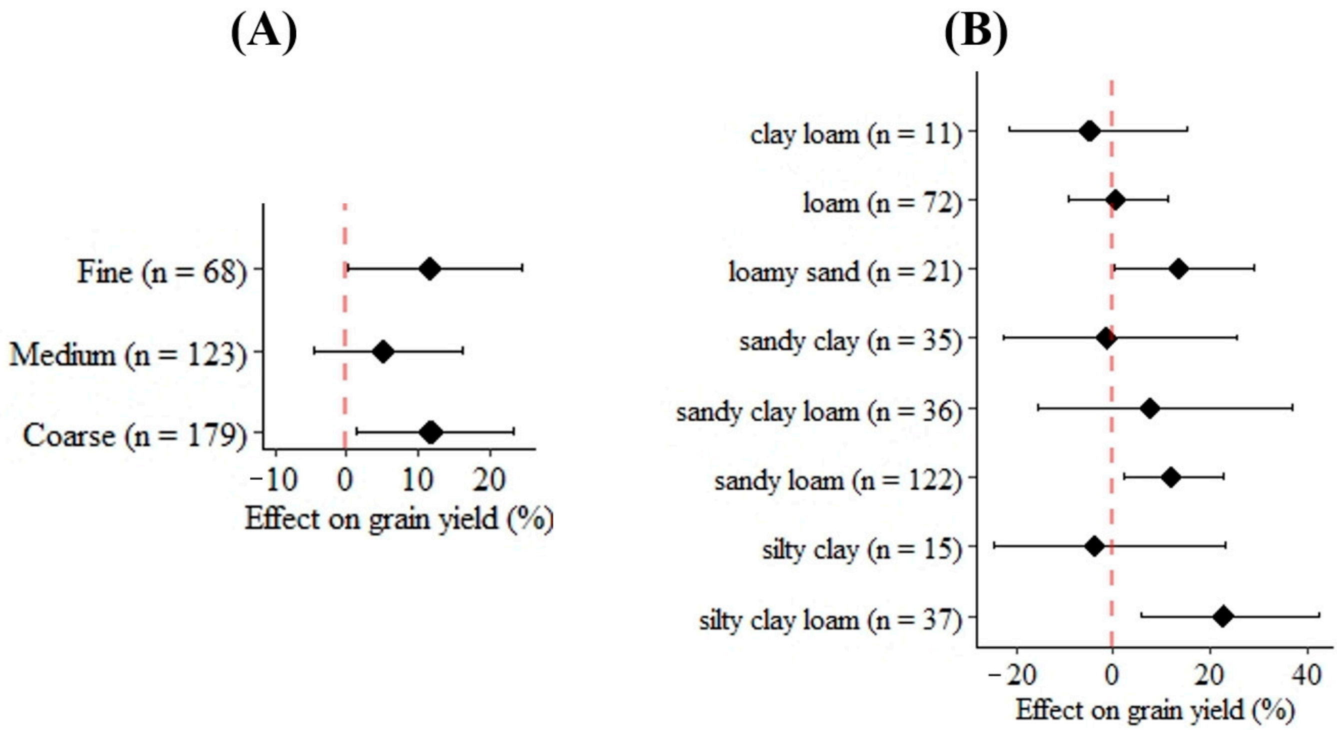

Figure 6. Forest plot for the crop yield response to cover cropping vs. bare fallow soil (CC vs. NC) (**A**) under different soil types, and (**B**) under different soil textures, expressed as the average effect size on crop yield (%). Numbers (*n*) in the parentheses are the number of observations for each subgroup. The vertical line represents the null hypothesis (ln (RR) = 0). The points (⧫) represent an estimate of effect size, and the horizontal lines are the associated 95% confidence intervals for the cover crop effect on grain yield.

3.6. Tillage Practice under Different Climate Conditions

The response of crop yield to cover cropping practice vs. fallow for the interaction between tillage practice and climate conditions is represented in Figure 7B. As previously reported in this study, a positive significant impact (+23%, *n* = 34 observations) was detected for CC on grain yield only for conventional tillage practice and only under Southern European climate conditions, and part of the overall observations.

It seemed that combining CC with conventional tillage (CT) was the most pronounced in Northern Europe as is demonstrated by the number of observations (*n* = 179) compared with other types of tillage. CC with the no-tillage technique (NT) was most represented in Southern European conditions (*n* = 54 observations). Under Northern European conditions, a positive and significant impact of cover cropping was detected only under NT practice (+16%, *n* = 13 observations). Under humid and cool conditions, the proper management of cover crops is necessary to reduce weed pressure and competition from cover crops which resulted in cash crop yield instability [103]. Salonen and Ketoja et al. [52] reported a limited effect of cover crops on weed suppression in organic cereal-based rotations under reduced tillage. However, Pittelkow et al. reported that yield increased strongly due to NT in a dry climate compared to the same practices in humid regions, for which yield decreased significantly for all conservation-tillage practices [104]. Moreover, a significantly high grain yield was detected under conventional (CT) and reduced tillage (RT) practices, under Southern

European conditions (+23%, *n* = 34 observations and +18%, *n* = 32 observations, respectively). Furthermore, a negative trend of cover cropping (−3%, *n* = 54 observations) was observed under NT in Southern Europe. In Southern Europe, Fogliatto et al. recommended hairy vetch for warmer climates in tilled soils because it is sensitive to cold conditions with a low emergence rate in NT practice [63]. Cold tolerance and fast strong early vigour are advised traits when choosing cover crop species [105]. Vincent-Caboud et al. also reported that cover crops with NT in southern parts of Europe are more implemented before summer cash crops [103]. Additionally, in Southern Europe, Adeux et al. reported that both tillage systems, CT and RT, with legume CC led to a high maize grain yield [64].

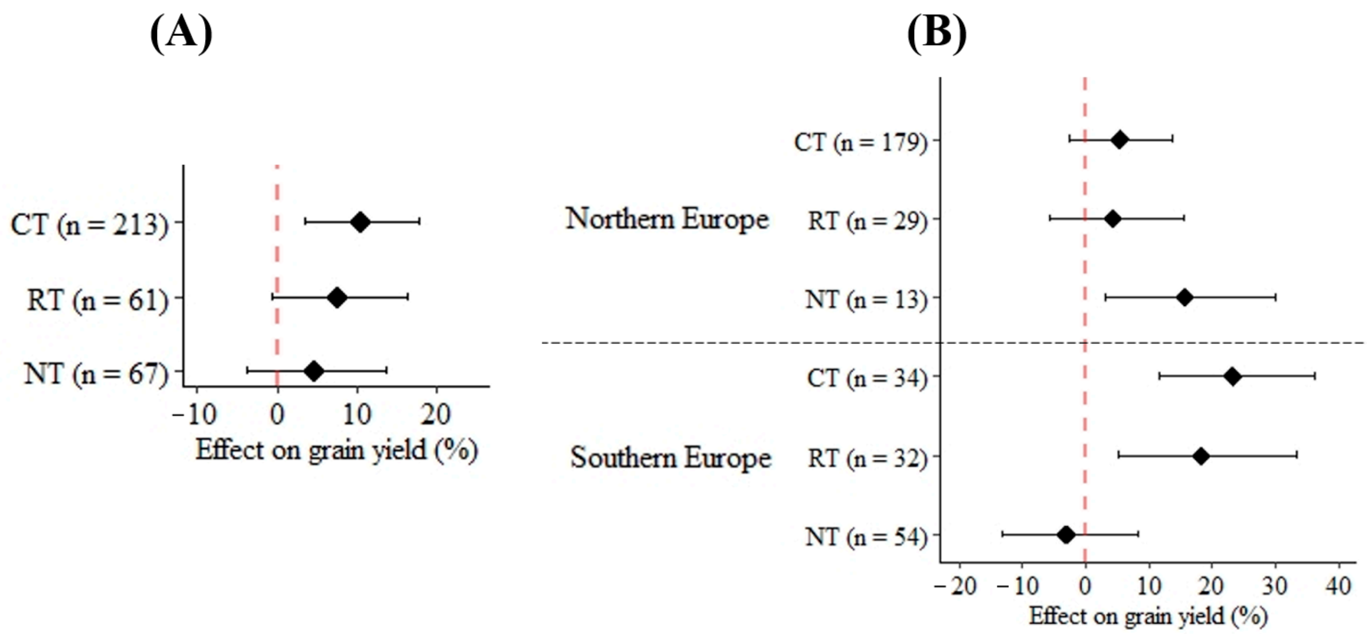

Figure 7. Forest plot for the crop yield response to cover cropping vs. bare fallow soil (CC vs. NC) (**A**) under three types of tillage practices, and (**B**) for the interaction between tillage practice and climate conditions, expressed as the average effect size on crop yield (%). Numbers (*n*) in the parentheses are the number of observations for each subgroup. The vertical line represents the null hypothesis (ln (RR) = 0). The points (♦) represent an estimate of effect size, and the horizontal lines are the associated 95% confidence intervals for the cover crop effect on grain yield.

3.7. Cash Crop Species

The crop yield response due to cover crops vs. fallow for different cash crops is reported in Figure 8. A positive significant impact of the cover crop compared to fallow on maize and oat grain yield (+12%, *n* = 152 observations and +16%, *n* = 39 observations, respectively). Our results showed a higher effect of cover crops on maize yield compared to the results of Wojciechowski et al. (2023) [106] who calculated an 8% increment of maize yield following cover crops summarized in a global meta-analysis from publications from 1967 to 2022 with a major effect of Fabaceae cover crops (+17%) among all cover crop botanical families (*Poaceae*, *Brassicaceae* and mixtures). As explained by Sieling 2019 [107], maize was able to optimally utilise N derived from cover crop residues due to its long growing period and, coincidently, N demand and supply from soil mineralisation. Furthermore, a positive impact on wheat crop yield (+8%, *n* = 89 observations), while a negative impact on barley crop yield (−0.5%, *n* = 81 observations) were observed, even if no significant differences were detected for both crops. Both legume and non-legume cover crops had a significant and positive effect on maize crop yield, while inconsistent results were detected for wheat crops [108].

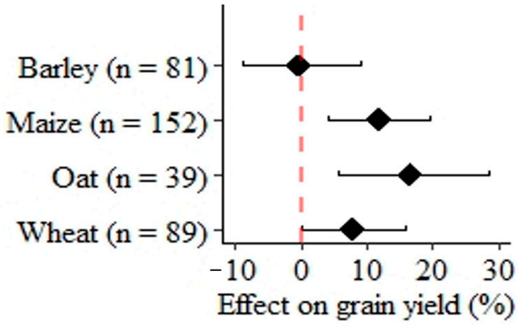

Figure 8. Forest plot for the crop yield response to cover cropping vs. bare fallow soil (CC vs. NC) for different cash crops, expressed as the average effect size on crop yield (%). Numbers (*n*) in the parentheses are the number of observations for each subgroup. The vertical line represents the null hypothesis (ln (RR) = 0). The points (⧫) represent an estimate of effect size, and the horizontal lines are the associated 95% confidence intervals for the cover crop effect on grain yield.

4. Conclusions

This meta-analysis indicates that cover cropping is a viable strategy for enhancing grain yield for cereal crops in Europe. In addition, this study summarized this effect across a range of crop species, climate and soil conditions, and other conservation farming management. The study demonstrated that legume cover crops led to the highest increase in grain yield for cereal crops. Cover crops from the *Brassicaceae* family also resulted in a positive impact on grain yield under Southern European conditions.

The results of this study showed that crop yields in diverse cropping systems were lower for medium soils compared to fine- and coarse-textured soils. Cover cropping affected the subsequent cash crop positively under conventional tillage practice. Given the negative impacts of conventional tillage on soil quality, and increased soil erosion potential, no or minimum tillage practices have become standard practice across much of Europe's cropping zones.

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