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Influence of Organic and Mineral Fertilizers on Soil Organic Carbon and Crop Productivity under Different Tillage Systems: A Meta-Analysis

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Abstract: The intensive use of mineral (M) fertilizers may cause harm the environment via leaching or greenhouse gas emissions, destroy soil fertility as a consequence of loss of soil organic matter, and, due to their high price, they are economically unviable for producers. It is widely accepted that organic (O) fertilizers may deal with pressing challenges facing modern agriculture, even if farmers need to improve their knowledge for applying in fertilization programs. A meta-analysis approach has been adopted to evaluate the effects on soil organic carbon (SOC) and crop yield of O fertilizers, applied alone or in combination with mineral fertilizers (MO) under conventional (CT), reduced (RT), and no-tillage (NT) regimes. The analysis was performed in different climatic conditions, soil properties, crop species, and irrigation management. Organic fertilizers have a positive influence in increasing SOC compared with M (on average 12.9%), even if high values were observed under NT (20.6%). The results highlighted the need for flexible and environment-specific systems when considering organic fertilization subjected to different tillage regimes. Similarly, MO application showed a better crop yield response in CT and RT under coarse soils when compared with M fertilizer applied alone (on average 13.4 and 12.7%, respectively), while in medium-textured soils, CT and RT yielded better than NT under O fertilizers (9.5 and 11.2 vs. 2.5%, respectively). Among the crop species, legumes performed better when O fertilizers were adopted than M fertilizers (on average 15.2%), while among the other crop species, few differences were detected among the fertilization programs. Under irrigated systems, RT and NT led to higher productivity than CT, especially under MO treatments (on average 9.2 vs. 3.4%, respectively). The results highlighted the importance of the environmental and agronomical factors and how their understanding could affect the impact of these conservation farming practices on crop productivity to improve the sustainability of the farming system in a specific region.

Keywords: sustainable cropping systems; fertilization source; soil tillage; crop yield response; soil health

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1. Introduction

The growing population associated with rising hunger stimulated the industrialization of agricultural practices that require increased use of farmland to produce the highest yield by means of intensive use mineral fertilizers and heavy soil tillage. Adopting these practices led to significant growth in agricultural productivity but came at the cost of environmental and soil health [1,2]. Indeed, the intensive applications of mineral fertilizer caused loss of soil organic carbon, environmental pollution, overexploitation of natural resources, loss of biodiversity, and adverse climate changes. In addition, chemical fertilizers are also criticized due to their effect on soil deterioration as their intensive use in agroecosystems to improve crop productivity causes a gradual modification of soil physical properties making soils acidic [3].

Recently, the concept of sustainable agriculture has been developed as a system of ecological farming practices based on scientific innovations to satisfy the needs of humankind for healthy foods, while maintaining the quality of the environment and the natural resources base. The adoption of organic fertilizers instead of mineral ones could represent an environment-friendly practice through sustainable farming systems. Indeed, organic fertilizers are obtained from organic materials (i.e., plant residues, animal manures, by-products of the food industry) and subjected to several processes, such as fermentation, drying, chopping, and composting [4,5]. It has been reported that using organic nutrient sources associated with natural pest control in diverse cropping systems will lead to better agroecosystem services [6]. In addition, plant residues or animal waste used have been used as organic fertilizers due to their richness of organic matter, improving soil structure and helping microbes thrive, and consequently providing nutrients to crop plants in a natural biological process. However, one of the main difficulties related to organic fertilizers is that since organic materials are variable in terms of quantity and quality, their content in macro and micro-nutrients are lower compared to inorganic fertilizers. This requires the adoption of excessive amounts of organic materials to respond to the nutrient demand to support high crop yields [7].

The reduction of soil carbon content observed in the agricultural fields has been due also to intensive and frequent tillage practices, which contribute to creating an aerobic environment in the soil that facilitates the mineralization rate of soil organic matter [8]. Although soil tillage is used for seedbed preparation, weed suppression, soil aeration, the management of crop residue and cover crop biomass, leveling the soil, incorporating manure and fertilizer into the root zone, intensive tillage passes fractures the soil, it disrupts the soil structure, facilitating soil crusting and erosion [9,10]. Conservation tillage represents another approach to sustainable agriculture that has been continuously evolving since the late 20th century with the main goal to address problems, such as soil erosion and degradation, meanwhile preserving natural resources. Nowadays, conservation tillage is one of the main pillars of conservation agriculture farming aimed to protect soils by permanent soil cover through previous crop residues or cover crops and reduce soil tillage process in diverse cropping systems. Several studies showed that the application of conservation tillage would lead to improving soil health by increasing water and nutrient use efficiency and reducing soil degradation. Moreover, agroecosystems managed under conservation agriculture practices may prevent further losses; at the same time, conservation can be used to re-establish degraded lands. Conservation agriculture has been practiced and promoted worldwide by applying conservation tillage practices, particularly because of expected benefits such as a decreased cost, labour intensity, and reduced greenhouse gases emissions. In addition, the FAO has reported that conservation agriculture is practiced worldwide, with an increase in the total area from 45 million ha in 1999 to over 200 million hectares in 2021 [11]. It is interesting to note that about half the areas adopting conservation agriculture are located in developing countries [12]. The reduction of tillage depth through reduced-tillage (RT) or no-tillage (NT) practices represents sustainable strategies of conservation agriculture. Overall conservation tillage systems protect soils, conserve soil moisture, and get the best benefits of previous crop residues.

Integrating organic fertilizer application with conservation tillage practices could be a suitable option for sustainable agriculture.

Various studies have been conducted to evaluate how sustainable farming management could be adopted to replace conventional or modern industrial farming and try to understand how different management systems may influence environmental health, soil structure and fertility, and crop productivity. Several authors report a reduction in greenhouse gas emissions [13,14], an improvement of soil quality [15,16], and, consequently, an enhancement of soil fertility [7,17], all while better maintaining biodiversity [18,19]. Despite that, often yield gap is reported as the main challenge for adapting these sustainable farming managements. Research reports confirmed that under certain conditions, the yields of sustainable and conventional farming practices could be equal, even if the effects of organic fertilization and conservation tillage practices are not well understood and widely accepted by farmers, given the wide range of conditions the agricultural activities are subjected.

Improving knowledge concerning the combination of organic fertilizers with tillage regimes may represent an important decision tool for the farmers that will arrange their activities based on the interaction of these farming practices with climatic conditions, crop rotation, crop choice, and soil characteristics. This meta-analysis study has been conducted to identify the implication of crop fertilization and soil tillage on crop yield and soil organic carbon (SOC). The study hypothesizes that farmer decisions, in terms of fertilization source and soil tillage, are variable and should be well integrated with the agricultural and environmental factors that characterize the agroecosystems. For this purpose, this study compared the use of organic fertilizers and conservation tillage (minimum tillage/no-tillage) related to mineral fertilizers and conventional tillage practices, respectively. The main aims of this meta-analysis are: (a) to investigate the effects of organic fertilizers applied alone or in combination with mineral fertilizers compared with conventional fertilized crops subjected to different soil tillage regimes; and (b) to study the impact of organic fertilizers and conservation tillage practices on yield and SOC responses under different climate conditions, soil characteristics, crop categories, and irrigation water management.

2. Materials and Methods

2.1. Data Collection

Literature searches were performed in SCOPUS using keywords (organic AND mineral AND fertilizer AND soil AND tillage AND crop AND production OR crop AND yield) AND [limit-to (article)] AND [limit-to (language, English)] AND [limit-to (exact keyword, "crop yield)]. The papers were assembled without duration limitation; they ranged from 1987 to 2020, and a cutoff of November 2021 was applied. The appropriate studies were selected using the following criteria: (1) three or more replicates per treatments; (2) means of original yield data available from tables, figures, and supplementary materials; (3) sound experimental design; (4) comparison between the organic (O) versus the chemical (M) fertilizers under the same field management and environmental conditions; (5) report the interaction effect of different fertilization sources under different tillage intensities on crop grain yield; (6) treatments must have been carried out at the same location; (7) no review or meta-analysis. Complete criteria for the assembled database and a complete list of references for all included studies are provided in Table 1. To take full advantage of the available data, we recorded multiple data points from a single study, including multiple years, different crop species, soil types, and climate conditions. These multiple comparisons also allowed to place the heterogeneity between different studies in the context of uncontrolled variations. To avoid bias, yield data reported for unnormal conditions were excluded from the analysis. Studies that reported the data averages of multiple years were given a higher weight. For each study, the following variables were collected: (1) research site coordinates; (2) type and rate of fertilizer adopted; (3) soil tillage practice; (4) cropping system as crop monoculture or crop rotation system (rotation system was considered when two or more crops were grown in sequence in the same field over time); (5) irrigation practices were divided into rainfed or irrigation. (6) soil classification based on the Natural Resources Conservation Service Soils USDA (https://www.usda.gov/ (accessed on 14 February 2022)) using the reported percentage of sand, silt, and clay; Three different categories were reported based on soil texture data: (i) fine (clay, silty clay), (ii) medium (silty loam, clay loam, sandy clay loam), or (iii) coarse (sandy loam, loamy sand); (7) climate conditions (tropical, semiarid, temperate, continental, subarctic). Climate conditions were taken either from other papers in the same location or from the online database (https://en.climate-data.org/ (accessed on 14 February 2022)) if not reported by the authors, based on the location of the study site. Climate conditions were grouped in three categories: (i) humid conditions (tropical, humid subtropical, humid continental conditions), (ii) dry subhumid conditions (semiarid tropical and Mediterranean conditions), and (iii) dry conditions (semiarid and arid conditions); (8) yield data were obtained from text, tables or extracted from graphics using the freeware Plot Digitizer http://plotdigitizer.sourceforge.net (accessed on 14 February 2022). If a publication reported results from distinct sites and each had its own properties, such sites were kept separate in our analysis.

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

Authors	Crop Species	Tillage System	Fert. Source	Response Variable
[20] Kumar et al. 2020	Cereal	CT, RT	M, MO	Yield, SOC
[21] Shumba et al. 2020	Cereal	CT, RT	M, MO	Yield, SOC
[22] Pradhan et al. 2020	Cereal, Legume	CT, RT	M, O, MO	Yield
[23] Ramachandrappa et al. 2019	Cereal, Legume	CT, RT	M, O, MO	Yield, SOC
[24] Siebou et al. 2019	Cereal, Legume	CT, NT	M, O, MO	Yield
[25] Somenahally et al. 2018	Cereal	CT, NT	M, O	Yield, SOC
[26] Sheoran et al. 2016	Cereal	CT, RT	M, O, MO	Yield
[27] Sharma et al. 2015	Cereal, Legume	CT, RT	M, O, MO	Yield, SOC
[28] Choulwar et al. 2015	Fiber	CT, RT	M, O, MO	Yield, SOC
[29] Huang et al. 2015	Cereal	CT, NT	M, MO	Yield
[30] Amegashie, 2014	Cereal	CT, RT, NT	M, O, MO	Yield
[31] Endale et al. 2014	Cereal	CT, NT	M, O	Yield
[32] Qadir Memon et al. 2014	Cereal	CT, NT	M, O, MO	Yield
[33] Mohammadi et al. 2013	Oilseed	CT, RT, NT	M, O, MO	Yield
[34] Patil et al. 2013	Cereal	CT, RT	M, O, MO	Yield
[35] Sankar et a. 2013	Cereal, Legume, Oilseed	CT, RT	M, O, MO	Yield
[36] Kumar et al. 2012	Cereal	CT, RT, NT	M, MO	Yield
[37] Watts & Allen Torbert, 2011	Cereal, Legume	CT, RT, NT	M, O	Yield, SOC
[38] Agbede, 2010	Root crop	CT, NT	M, O, MO	Yield, SOC
[39] Montemurro, 2009	Cereal	CT, RT	M, O, MO	Yield
[40] Reddy et al. 2009	Fiber, Cereal	CT, NT	M, O	Yield
[41] Nema et al. 2008	Cereal	CT, RT	M, O, MO	Yield
[42] Tewolde et al. 2008	Fiber	CT, NT	M, O, MO	Yield
[43] Ouedraogo et al. 2007	Cereal	CT, NT	M, O, MO	Yield, SOC
[44] Khan et al. 2007	Cereal	CT, NT	M, MO	Yield, SOC
[45] Pendell et al. 2004	Cereal	CT, NT	M, O	Yield
[46] Reddy et al. 2004	Fiber	CT, NT	M, O	Yield
[47] Hook, 1999	Fiber	CT, NT	M, O	Yield
[48] Eghball & Power, 1999	Cereal	CT, NT	M, O	Yield
[49] Stevenson et al. 1998	Cereal, Oilseed	CT, NT	M, O	Yield
[50] Blumberg et al. 1997	Cereal	CT, NT	M, O	Yield
[51] Weill et al. 1989	Cereal	CT, RT, NT	M, O	Yield
[52] Groffiman et al. 1987	Cereal	CT, NT	M, O	Yield

CT: conventional tillage; RT: reduced tillage; NT: no-tillage, M: mineral fertilization; O: organic fertilization; MO: mineral + organic fertilization; SOC = Soil Organic Matter.

2.2. Study Summary and Characteristics

Two datasets were realized: (1) (O vs. M) included studies that evaluated the effects of using O instead of M (n = 423), and (2) (MO vs. M) compared MO also with M (n = 357) on grain yields (Figure 1). The computed effect sizes in both datasets were normally distributed (Figure 2). Yield pair observations represent 50 studies from 28 publications, and 44 studies from 20 publications for (O vs. M) and (MO vs. M), respectively. Data from twelve publications were included in both datasets. The descriptions of all study characteristics and categories are displayed in Table 1. Studies from eleven publications for O vs. M were conducted in the USA; ten of these publications evaluated that difference under CT and NT, while only one included CT and both conservation tillage practices RT and NT. Moreover, studies from eight publications for O vs. M were carried out in India, all of them compared that difference under CT and only RT, six of them have included two tillage intensities of RT (RT1 and RT2 in this study). Most of the publications for MO vs. M were included studies conducted in India. Most of them included more than one crop in their experiment; one of them even examined the effect of these farm managements on four different crop species. Overall, twelve different crops were included in India (mostly cereals and legumes), and only five crops in the USA (mostly cereals and cotton). In addition, all studies carried out in India included MO as a potential strategy to reduce M fertilizers. More than 80% and 90% of the studies were collected from studies using rotation cropping systems for (O vs. M) and (MO vs. M), respectively. At the same time, more than 90% and 80% of the studies were collected from studies under rainfed conditions for (O vs. M) and (MO vs. M), respectively. All the databases represent studies from 12 countries around the world, on 13 different crop species in seven different soil textures. Studies were mostly excluded because the interaction effects of tillage and fertilization management on grain yield were not reported.

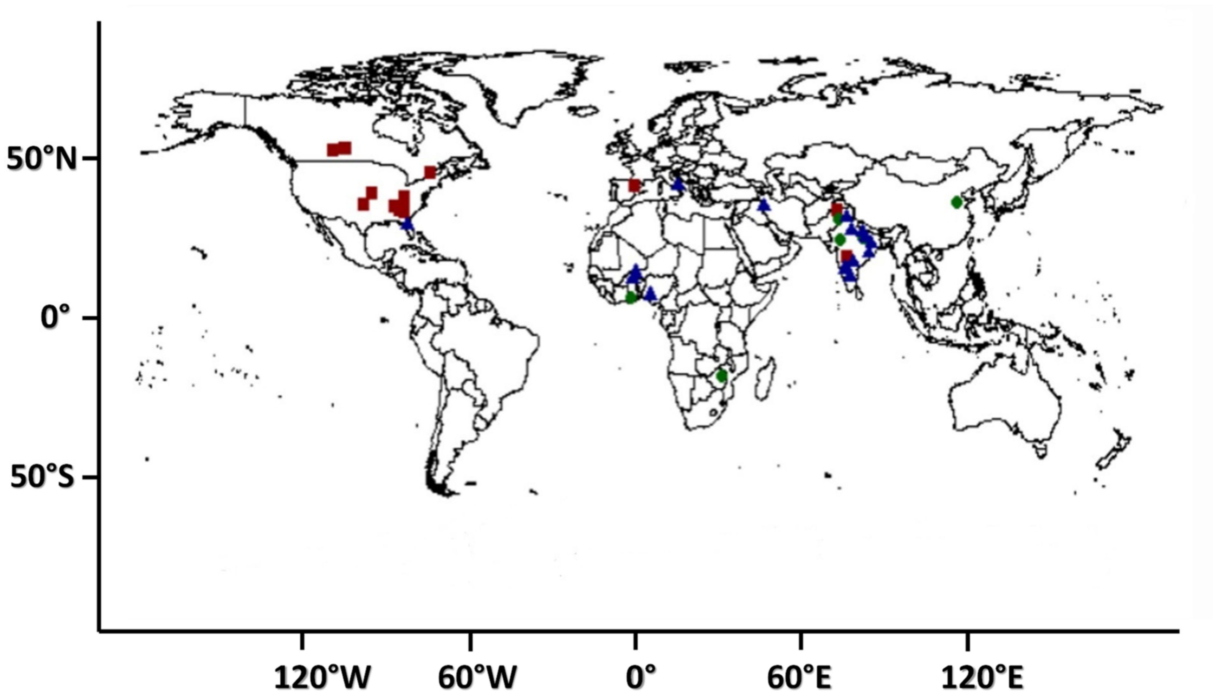

Figure 1. Locations of the studies included in the meta-analysis according to their longitude and latitude. Locations of studies evaluated only organic (O) versus inorganic (M) nutrient sources, were presented by [■], and studies evaluated only combined organic and inorganic (MO) versus inorganic (M) nutrient sources were presented by [•], and finally studies evaluated both O and MO versus M were presented by [▲].

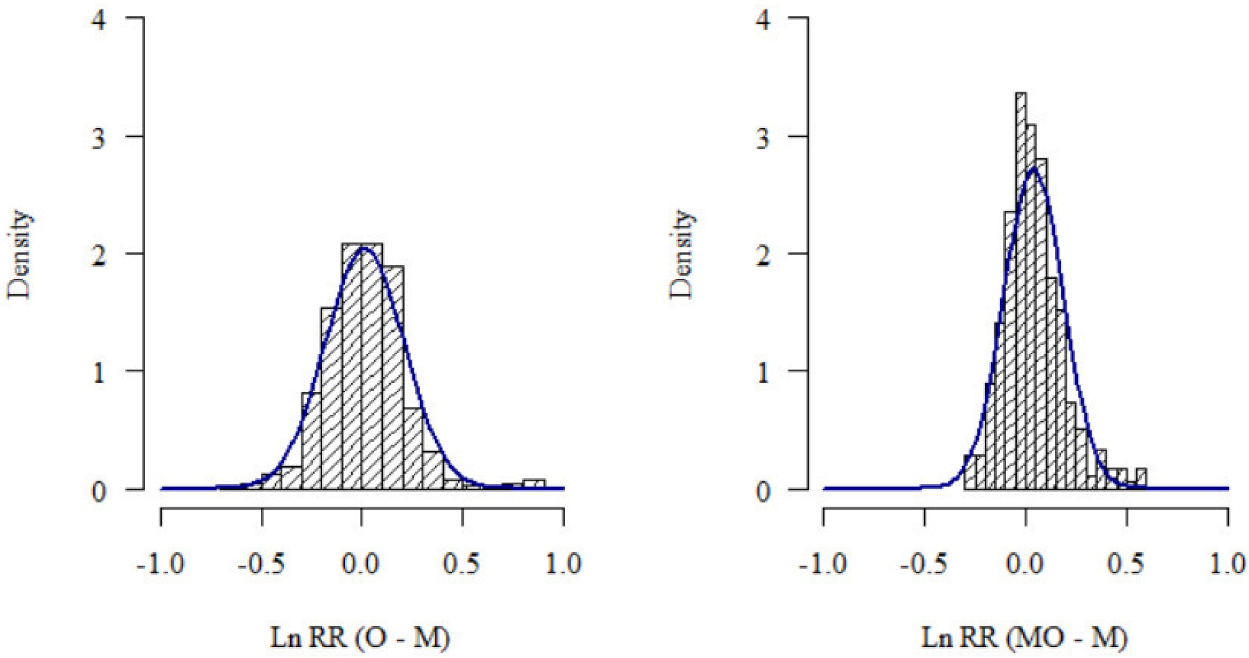

Figure 2. Normal distribution of the effect of O or MO compared to M on crop productivity (effect size).

2.3. Data Analysis

Crop yield paired observations under different farming management and environmental conditions were collected. A random-effect meta-analysis was performed to explore environmental and management variables that might explain the response of crop yield to O or MO. The response ratios (*RR*) for each of O or MO versus M were calculated as follows:

$$RR = \frac{X_{O/MO}}{X_M}$$

where $X_{O/MO}$ is the crop yield average for the experimental group O or MO, respectively, and X_M is the crop yield mean for the control group M. The statistical analysis was performed using the natural logarithm of the effect size *RR* (*lnRR*), which was calculated for each observation/study [53]. The variance of the response ratio v_i was calculated using the equation:

$$v_i = \frac{SD^2{}_{O/MO}}{X^2_{O/MO}\,N_{O/MO}} + \frac{SD^2{}_M}{X^2_M\,N_M}$$

where the standard deviation $SD_{O/MO}$, the sample size (number of replicates) $N_{O/MO}$ for the experimental group, and the standard deviation and the sample size of the outcome in the control group by SD_M and N_M, respectively. Outliers were identified based on a plot of influence diagnostics outliers. Effects sizes within the meta-analysis were weighted (w) using the inverse of the variance (v_i) of each individual study (i) computed as [53]:

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

Eventually, the weighted mean effect size $\overline{\text{lnR}}$ was estimated as:

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

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

$$95\%\ \text{CI} = \overline{\ln R} \pm 1.96\ \text{SE}_{\overline{\ln R}}$$

where $\text{SE}_{\overline{\ln R}}$ is the standard error of $\overline{\ln R}$ was computed as:

$$\text{SE}_{\overline{\ln R}} = \sqrt{\frac{1}{\sum w_i}}$$

The percent change in selected variables was computed using the equation:

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

SD was estimated as 0.1 times the mean for studies that did not report SD [54].

There were a few studies that reported SOC measurements, which allowed the investigation of the effect of these farming practices on Soil Organic Carbon (SOC) as a soil quality indicator. The effects of partly or totally depending on organic fertilizers under different tillage systems on SOC were studied. All collected measurements for SOC were uniformly converted to the same units (g C kg^{-1}). In some studies, no bulk density (BD) was reported. In these cases, typical values of BD according to soil textures categories were used [55].

Values reported as Mg C ha^{-1} or % SOC were converted using the following equations:

SOC_t concentration (Mg C ha^{-1}) to SOC_g concentration (g C kg^{-1}):

$$SOC_g = (SOC_t \times 10)/(BD \times Dp)$$

SOC_p concentration (%) to SOC_g concentration (g C kg^{-1}):

$$SOC_g = SOC_p \times 10$$

where BD is the bulk density (g cm^{-3} or Mg m^{-3}) and Dp is soil sampling depth (cm).

The mean effect sizes for SOC responses were calculated using the natural log of the response ratios *RR* for each of O or MO instead of M fertilizers. In addition, the 95% confidence interval (CI) and % change were calculated following the same equations used for crop yield.

Crop yield and SOC differences for each subgroup were considered significant at a *p*-value of 0.05. A forest plot [56] was used to summarize the effects on grain yield. Subgroup analyses were conducted to assess the effect of tillage practices along with climate conditions, soil properties, and crop category on yield response. The meta-analysis was performed using the restricted maximum likelihood estimator (REML) estimation in the rma.mv model of the 'metafor' package [57] programmed using the R statistical software language [58].

3. Results and Discussion

Soil characteristics are subjected to important modifications based on the tillage system adopted; therefore, the choice of appropriate fertilizer source and tillage operations should be addressed based on climate conditions, soil conditions, type of crops, and management factors [59]. The results of subgroup analysis for each categorical variable (described in Table 1) are separately presented in this study.

3.1. Soil Organic Carbon

The differences of using organic fertilizer (O) or the combination of mineral plus organic fertilizers (MO) instead of mineral fertilizers (M) under different tillage systems on soil organic carbon (SOC) are reported in Figure 3. The soil organic carbon represents a key factor for the soil fertility of agroecosystems, and all agricultural practices that affect the modification of SOC in the agricultural soil should be carefully considered to avoid dangerous environmental changes [60]. Improving the content of organic matter in the soil could be an efficacy strategy to mitigate climate changes and make resilient agroecosystems [61]. As expected, the data showed a positive impact on SOC when O fertilizers are adopted alone or in combination with mineral fertilizer (MO) to replace M fertilizers regardless of all tillage intensities (on average 13.0 and 9.1%, respectively), in agreement with previous studies [62,63]. In a recent piece of research, Rong et al. [64] reported a positive relationship between C input and soil C accumulation, thus meaning that soil carbon accumulation is strongly affected by fertilization programs and the application of organic fertilizers have a positive influence on the increase in SOC. In fact, the application of organic fertilizers supplies the needed substrate for soil microorganisms that are converted into soil organic matter [64]. Similarly, the application of mineral fertilizers may contribute to increasing the SOC in the soil by favoring the accumulation of plant biomass, even if a higher rate of mineral fertilizers rich in nitrogen stimulates the decomposition processes and, thus, determine a progressive depletion of the soil organic matter [65]. This could be the reason why the increase in soil organic matter is higher when organic fertilizers are applied alone (O) compared to their application in combination with mineral fertilizers (MO).

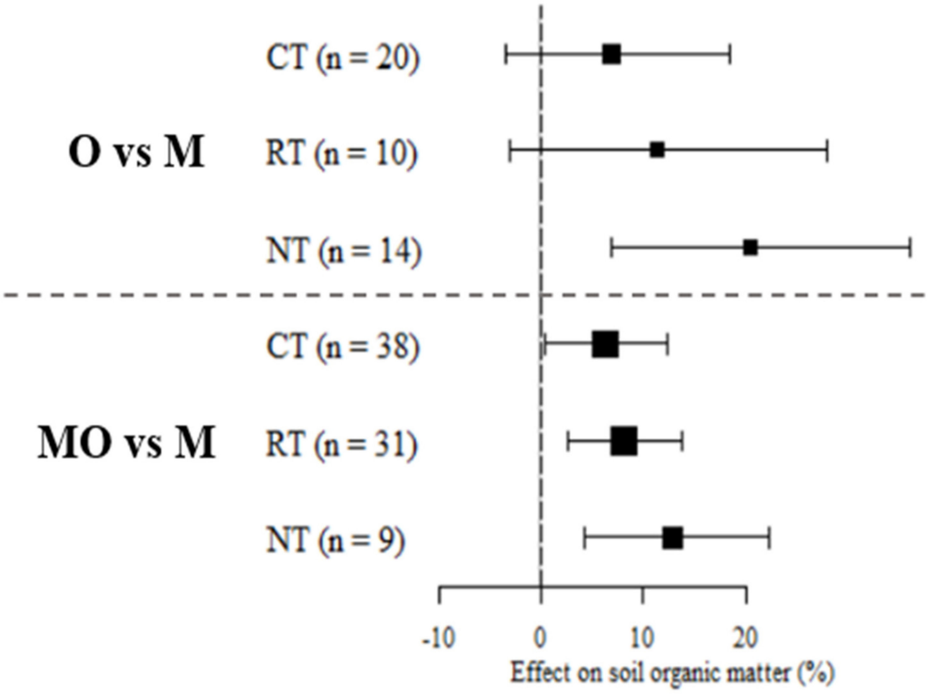

Figure 3. The soil organic matter (SOM) response of organic vs. mineral (O vs. M), and mineral + organic vs. mineral (MO vs. M) under conventional, reduced, and no-tillage practices (CT, RT, and NT, respectively), expressed as the average effect on soil organic carbon (%). "n" refers to the number of observations for each subgroup. The vertical line represents the null hypothesis [$ln(RR) = 0$]. The squares are the point estimate of effect size. The horizontal lines are the associated 95% confidence interval for the population parameter.

The analysis showed that there is a general trend of increasing SOC concentrations when reducing soil tillage intensity, either using O or MO instead of M fertilizers. Some research reports that conservation tillage practices have been recently supported mainly due to preserving soil health and increasing their fertility [66–69]. Indeed, reduced tillage practices aim to maintain SOC in the topsoil due to reduced contact with soil microorganisms and all related oxidation processes [13,70]. Accordingly, in this study, reduced tillage practices (RT or NT) have increased SOC in comparison with the conventional practice (CT) regardless of the fertilization source adopted (on average 6.6, 9.8, 16.7% in CT, RT, and NT, respectively). Significant effects were detected on SOC when using O fertilization under NT practices (20.6%). Under MO fertilization, the SOC enhancing was about 6.3%, 8.1%, and 12.9% in CT, RT, and NT, respectively. These results provide evidence that conservation agriculture is related to organic nutrient sources combined with conservation tillage practices for improving soil quality through increasing SOC.

3.2. Climate Conditions

The response of fertilizer source comparisons (O vs. M and MO vs. M, respectively) on crop yields subjected to different soil tillage regimes (CT, RT, and NT, respectively) under dry, dry subhumid, and humid climate conditions are presented in Figure 4. In agreement with the statement of Hammed et al. [71], climatic conditions could affect the performance of crops subjected to different fertilizer sources and, therefore, improving our understanding of crop responses to fertilizer sources under different climate variations will support practices in climate-smart farming systems by reducing the nutrient loss and improving the nutrient use efficiency.

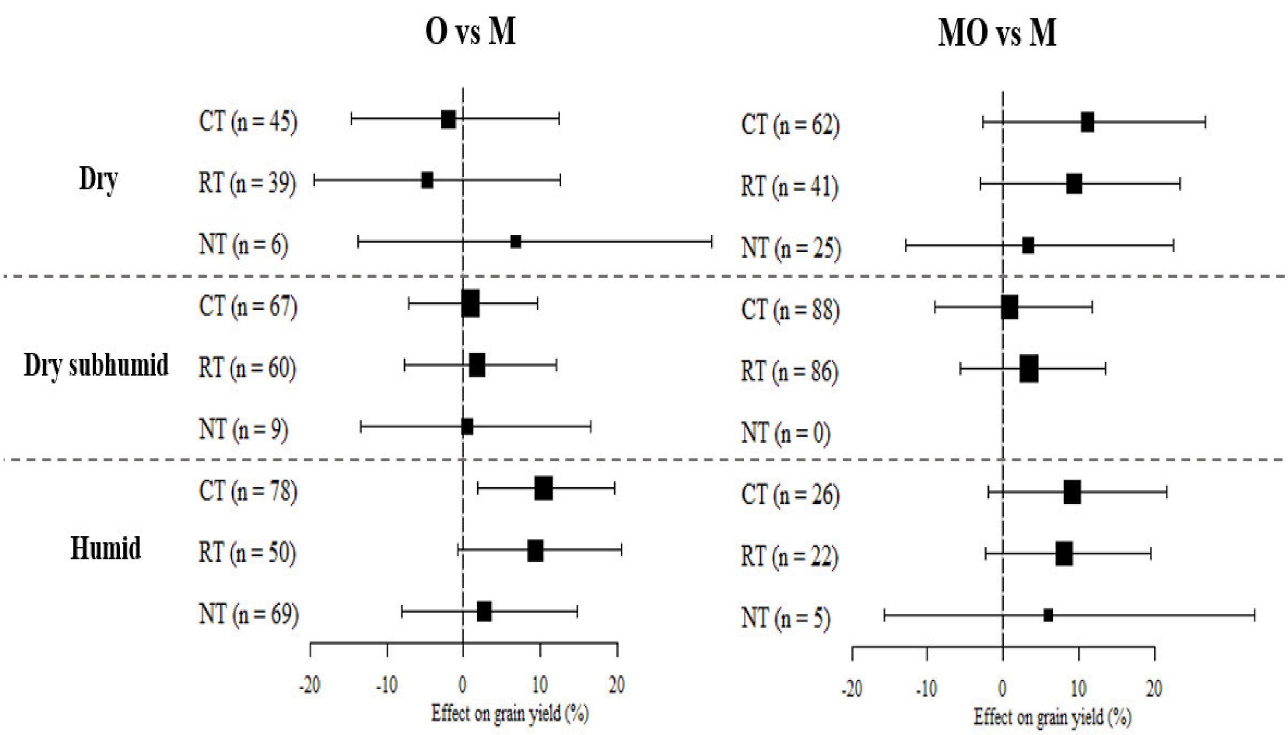

Figure 4. The crop yield response of organic vs. mineral (O vs. M), and mineral + organic vs. mineral (MO vs. M) under conventional, reduced and no-tillage practices (CT, RT, and NT, respectively) in different climatic conditions expressed as the average effect on crop yield (%). "n" refers to the number of observations for each subgroup. The vertical line represents the null hypothesis [$ln(RR) = 0$]. The squares are the point estimate of effect size. The horizontal lines are the associated 95% confidence interval for the population parameter.

In dry climate conditions, O fertilizers applied alone led to negative yields under CT and RT tillage regimes (−2.0 and −4.8%, respectively). Soil tillage may contribute to soil compaction, soil erosion, and excessive organic matter mineralization, that in the long-term period could determine a loss of soil productivity and fertility [72]. Conversely, crop yield under NT resulted higher compared with M fertilizer (6.8%), even if this result should be taken into consideration due to the limited number of observations (Figure 4). Several studies reported higher crop yield often reported for NT in dry conditions compared with CT [9,73,74]. The higher yield response of crop fertilized with organic fertilizers observed in NT tillage compared to RT and CT soil tillage under dry conditions could be due to a better status of soil microbes. Recently, Schmidt et al. [75] observed that the adoption of no-tillage practices shifted the microbial communities toward an increase in stress-tolerant microbes that may support the crop response to adverse agro-environmental conditions. In addition, Wang et al. [76] observed that the application of organic fertilizers in arid environmental conditions contributes to improving soil porosity and structure with an improvement on the water use efficiency and soil water infiltration. Conversely, tillage practices may threaten agroecosystems in arid and semi-arid environmental conditions due to negative modifications of soil properties [77]. Indeed, intensive tillage frequently repeated over a short period in the same soil can determine a gradual degradation of soil structure and reduce the stability of soil aggregates that lead to reduced soil water availability and soil erosion and compaction [78]. In addition, the application of mineral fertilizers and their improper management in dry climates may cause damage to soil fertility with negative consequences for the overall system [79,80]. The results showed as the application of organic fertilizers in combination with mineral fertilizers (MO treatment) in dry environments showed higher crop yield when compared with mineral fertilizers applied alone (M treatment), supporting the idea that intensive use of mineral fertilizer may have negative effects on plant growth and yield, but the application of organic fertilizer could alleviate these problems [81]. Similarly, Nouraein et al. [77] observed that the combination of organic fertilizers and balanced mineral fertilizers affects the soil characteristics in terms of enhanced structural stability and increased soil biological activity.

A positive yield trend was observed in dry subhumid and humid environmental conditions, where the adoption of organic fertilizers showed slightly higher crop yield under all soil tillage regimes, even if these effects were mostly not statistically significant. Significant impact was only detected under humid conditions, where CT was superior compared with other tillage practices (on average 10.4 vs. 6.1%, respectively). Moreover, a positive tendency under all tillage systems in both dry subhumid and humid climate conditions when depending on MO as a nutrient source (on average 16.0 and 7.7%, respectively). However, these trends were also not statistically significant. RT showed higher crop yield than CT in dry subhumid conditions (2.6 vs. 0.9%, respectively), particularly when using MO fertilizers (Figure 4), while no observations were available under NT. In agreement with Hijbeek et al. [82], crop yields in humid environmental conditions had more benefits from organic nutrient sources (Figure 4). Under humid environmental conditions, higher crop yield using O could be explained by higher nutrient mineralization and better soil aeration in conventionally tilled soils. According to the findings of Mancinelli et al. [13,83], soil tillage increases the mineralization rate releasing mineral nutrients available for crop nutrition supporting crop yield. However, De Ponti et al. [84] reported that site-characteristics significantly affect the yield gap between organic and mineral fertilizer sources, especially small yield gap was observed in humid environmental conditions. Overall, the results showed that climate conditions have more influence on grain yield when depending on organic sources alone, than combining both organic and inorganic fertilizers, both in comparison with inorganic sources alone. The results highlighted the need to be flexible and environment-specific when considering conservation or reduced tillage and the use of inorganic fertilizers.

3.3. Soil Properties

Several studies have shown that soil properties and texture are crucial for nutrient availability, especially nitrogen, that is released by means of the mineralization process of organic matter. Overall, soil texture represents a key factor for controlling the soil organic carbon stocks in a specific climatic area [85]. On the other hand, in a previous study on maize crop yield where O fertilizers are compared to MO fertilization management, it has been reported that soil textures had large effects on crop yield [86]. Crop yield responses to organic fertilization and organic plus mineral fertilization against mineral fertilization programs subjected to different tillage practices (CT, RT, and NT) under coarse, medium, and fine soil textures are reported in Figure 5. The analysis showed that in coarse and medium soils, crop yield responses were higher when using O or MO fertilization programs in comparison with M fertilizer applied alone, regardless of the adopted tillage regime (on average 5.8 and 8.4%, respectively). A significant positive impact was detected using O alone in medium soils only under CT and RT (9.5 and 11.2%, respectively), while significant impacts were found in coarse soils using MO sources under both CT and RT (13.4 and 12.7%, respectively). Similarly, the findings of Lin et al. [87] showed as the adoption of O fertilizer sources under various agricultural practices on crop yield productivity comparable to mineral fertilizer sources, even if under medium-textured soils it was observed a greater crop yield advantage compared with heavy and light-textured soils. In agreement with the results of this study, Allam et al. [88] reported that in comparison with fine soils, O fertilizers alone or combined with M fertilizers under the RT system improved soil structure properties in coarse and medium soils, which leads to considerable yield benefits. The application of organic fertilizers combined with the tillage treatments showed great potential to affect soil microstructure, and, thus, water and nutrient availability for crop growth and yield [89]. Reducing tillage intensity through the application RT or NT tillage regimes in this study led to higher yield in medium soils using MO fertilizers (8.4 and 11.4% in RT and NT, respectively, Figure 5). In fine soils, on the other hand, a negative trend using O fertilizers alone and no trend was detected using MO fertilizers under all tillage practices were detected in this study.

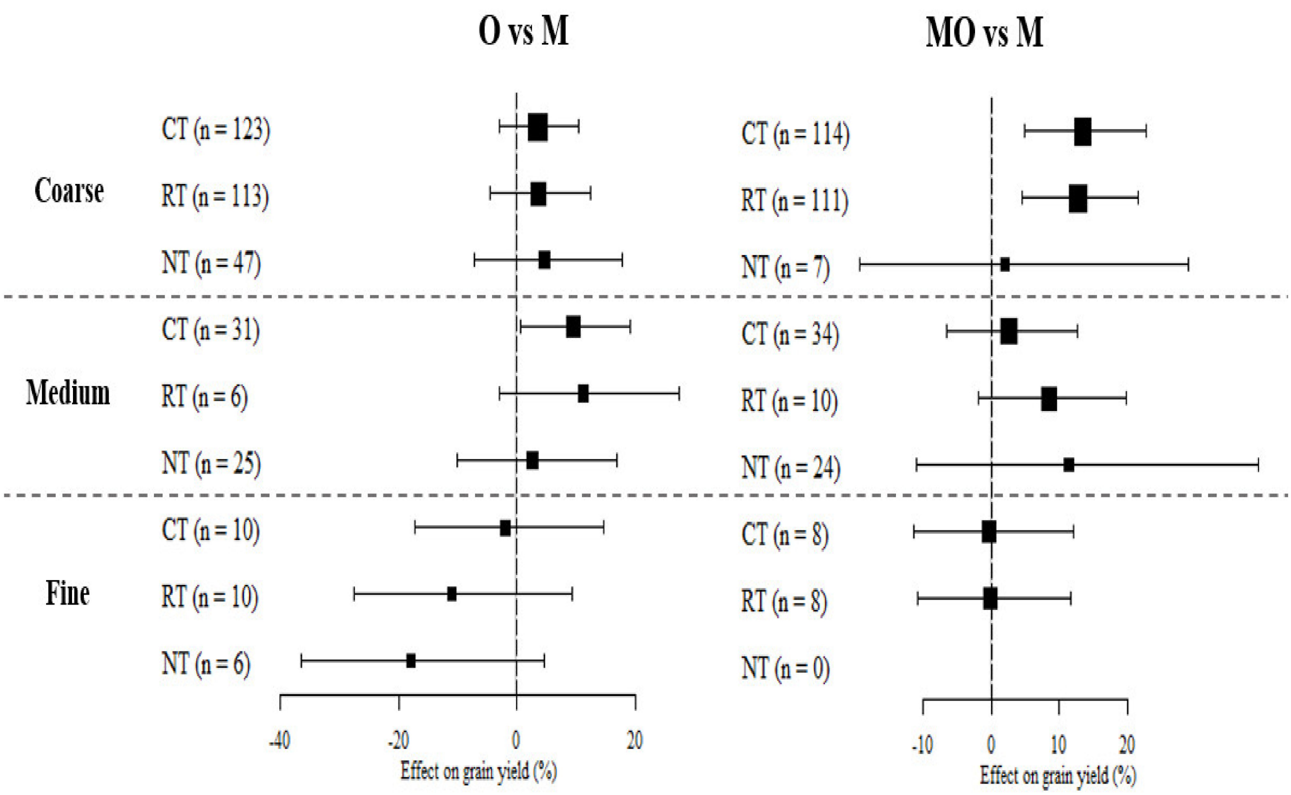

Figure 5. The crop yield response of organic vs. mineral (O vs. M), and mineral + organic vs. mineral (MO vs. M) under conventional, reduced, and no-tillage practices (CT, RT, and NT, respectively) in different soil types, expressed as the average effect on crop yield (%). "n" refers to the number of observations for each subgroup. The vertical line represents the null hypothesis [$ln(RR) = 0$]. The squares are the point estimate of effect size. The horizontal lines are the associated 95% confidence interval for the population parameter.

In fine soils, a negative impact was detected when using O fertilizer alone under all tillage practices (on average −10.7%), even if the negative impact on crop yield response was not observed when applying O fertilizers combined with M fertilizers (MO treatments, Figure 5). The high clay content in fine-textured soil determines compaction, especially during wet conditions, and thus may initiate serious sealing formation encouraging the adoption of soil tillage to physical improvement to support crop establishment and yield [17]. In addition, fine-textured soils have a greater ability to physically protect organic matter in the soil and, therefore, the addition of organic sources by fertilization practices in already organic-rich soils negatively affect crop yield response, as observed by Singh et al. [90]. In addition, a positive impact on crop yield response under conservation tillage systems (NT) on coarse and medium-textured soils and negative on fine soils was also reported by Rusinamhodzi et al. [91].

3.4. Crop Categories

The crop yield response due to fertilizer source comparisons (O vs. M and MO vs. M, respectively) subjected to different soil tillage under different crop species are reported in Figure 5. Although crop categories could differ in deep-rooted and shallow-rooted crops and thus determining different soil tillage requirements, in this study, all crop species showed a positive trend regarding using O or MO sources under all tillage intensities, except for fiber crops that generally showed a negative impact, even if no significant differences were detected (Figure 6).

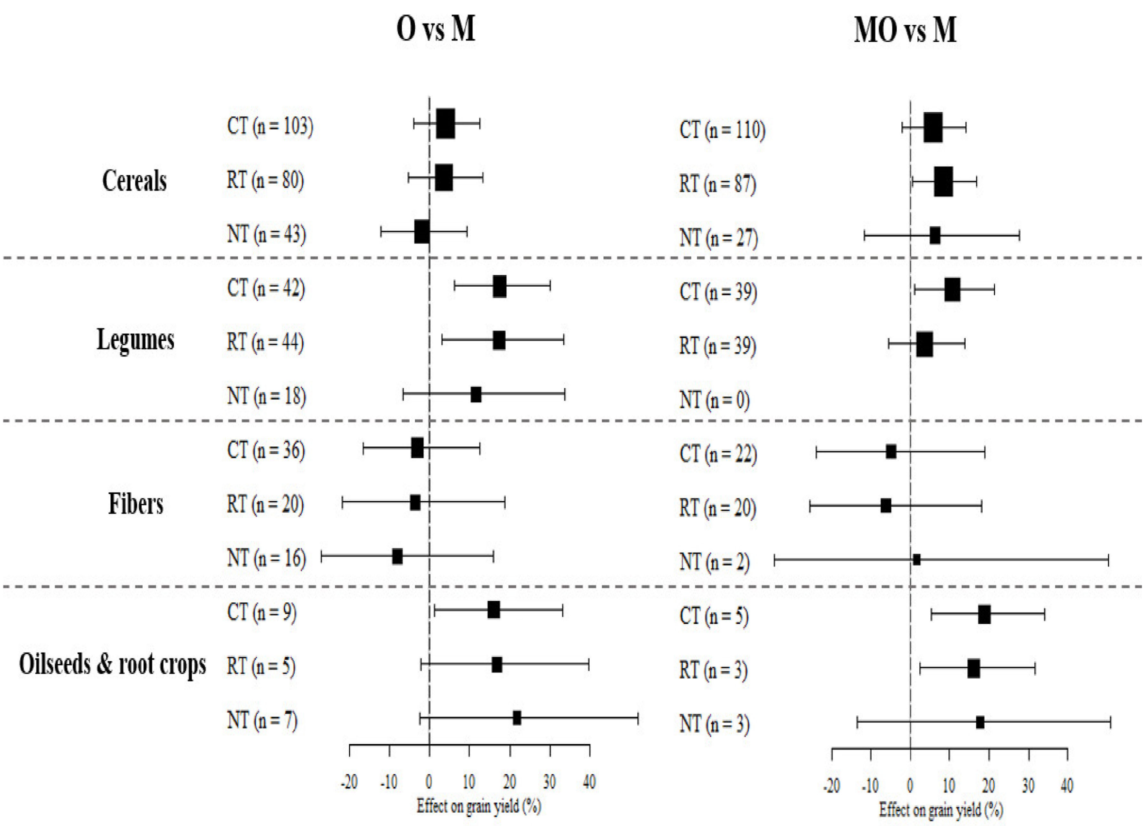

Figure 6. The crop yield response of organic vs. mineral (O vs. M), and mineral + organic vs. mineral (MO vs. M) under conventional, reduced and no-tillage practices (CT, RT, and NT, respectively) in different crop categories, expressed as the average effect on crop yield (%). "n" refers to the number of observations for each subgroup. The vertical line represents the null hypothesis [$ln(RR) = 0$]. The squares are the point estimate of effect size. The horizontal lines are the associated 95% confidence interval for the population parameter.

A significant positive impact was reported for cereals using MO under the RT system (8.4%), while a negative trend was observed for cereals only using O fertilizer sources under NT (−2.0%). The application of MO seems to be the best option for higher grain yield for cereals under RT. The combined application of inorganic (M) and organic (O) fertilizers has led to increased cereals yield compared to M or O fertilizers alone [86,92]. Similarly, Campiglia et al. [93] observed that durum wheat yield was similar among conventional and reduced tillage, especially in organic cultivation, and therefore concluded that the adoption of reduced tillage practices for durum wheat cultivation was preferable because it supported the reduction of intensive tillage.

Under the O fertilizers, the legumes yield response was significantly greater under both CT and RT regimes (on average 17.5 and 17.4%, respectively), while no significant response was observed under NT (Figure 6). Similarly, Zingore et al. [94] showed a higher performance of soybean crops when organically fertilized compared with mineral fertilization. The great yield response to organic fertilization was mainly attributed to the enhanced soil conditions needed for legume performance [95]. In addition, legumes can fix atmospheric N; thus, it is not a limiting nutrient for them, and consequently, they are more tolerant to the mineralization process in comparison with cereals crops. The application of MO fertilizers could give significant benefits for legumes only under CT techniques, but no significant response was found under RT; no observations were collected from experiments that evaluated legumes using MO and NT in our study. In pea crops, Faligowska et al. [96] observed higher grain yield in conventionally tilled soil compared to no-tillage, suggesting that these differences could be related to different biological and physical properties between the different tillage regimes. The previously mentioned study evaluated the impact of using O versus M on yields under various agricultural practices [87]; it has also been reported that legume crops performed significantly better when using an O source, with a positive pattern similar to this study was noticed over all crop species. Similarly, under organic farming managements, Cooper et al. [97] have reported that legumes were the best performed when reducing tillage intensities.

The yield response of fiber crops was positive only with MO under NT (1.8%), even if this result is limited due to a very small sample size (n = 2), in accordance with the findings of Idowu et al. [98] that reported several benefits of reduced tillage in cotton crop. Moreover, oilseeds and root crops showed a significant increase in grain yield using O with CT (21.8%) and MO with CT and RT (18.8 and 16.2%, respectively). A recent study showed as the seed yield of oilseed rape slightly varied according to the soil tillage regime suggesting the adoption of reduced tillage practices for this crop in order to improve economic benefits for the farmers [99].

3.5. Water Managements

The impact of using O or MO instead of M fertilizers under different tillage systems on crop yield response under two rainfed and irrigated conditions is reported in Figure 7. Water represents one of the main limiting factors for crop production, and a rational fertilization strategy should consider soil water availability to improve crop yield in a sustainable way, according to the findings of Liu et al. [100]. The analysis showed a positive trend under all tillage practices under both irrigated and rainfed systems, even if the only significant impact was detected under rainfed conditions using MO and CT (10.0%). Celik et al. [101] reported improved soil physical properties when organic materials were added to the soil, while Nyamangara et al. [102] observed a better soil water retention capacity when cattle manure was applied to agricultural soils. It is conceivable that the application of organic fertilizer applied alone or in combination with mineral fertilizer benefits rainfed agroecosystems because it maintains the soil water storage balance, supporting an increased availability of soil water for crop growth and yield compared to mineral fertilization programs [103]. Although no differences were detected among the tillage regimes, the lower crop yield response observed in NT than CT and RT could be a result of high variability and unequal distribution of rainfalls that cause high loss of nutrients, especially nitrogen, mineralized from O fertilizer sources [93]. The study suggests that under rainfed conditions, when depending on O or MO nutrient sources, RT is more suitable than NT for ensuring higher crop yield.

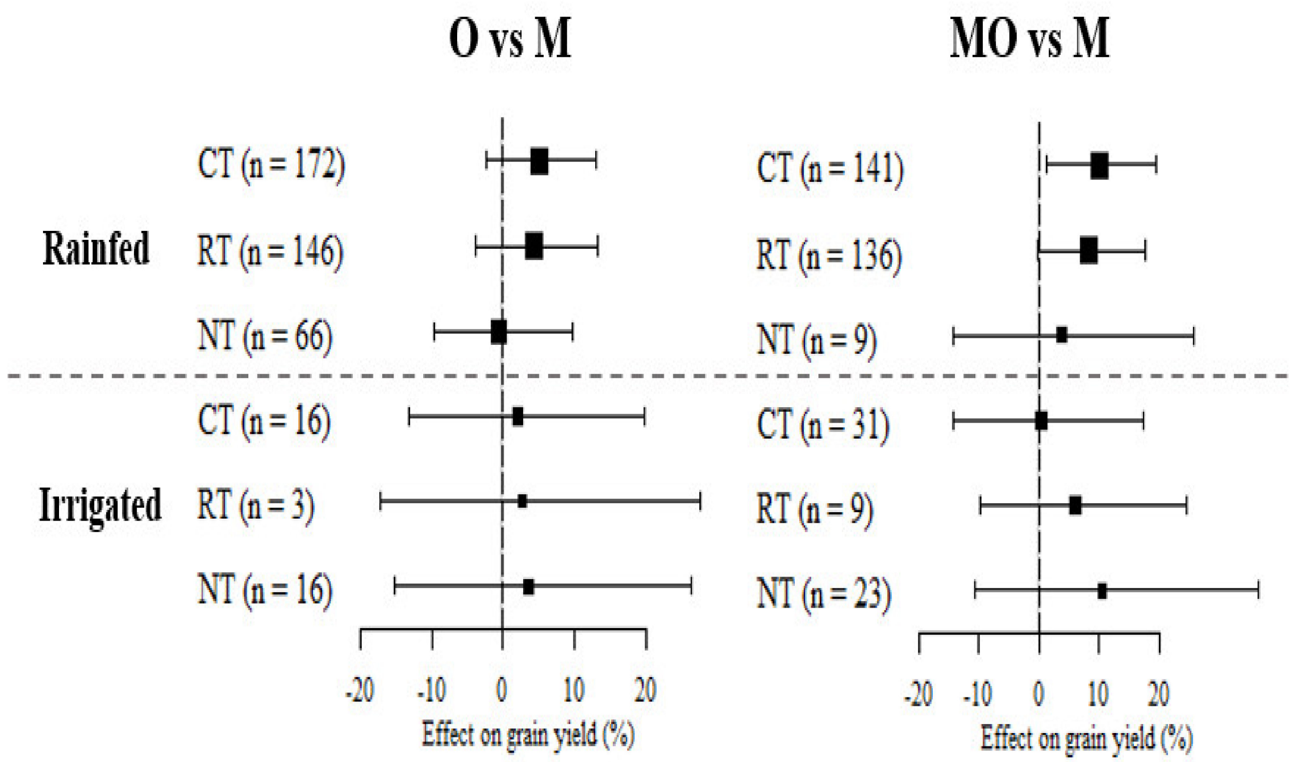

Figure 7. The crop yield response of organic vs. mineral (O vs. M), and mineral + organic vs. mineral (MO vs. M) under conventional, reduced and no-tillage practices (CT, RT, and NT, respectively) in different irrigation regimes, expressed as the average effect on crop yield (%). "n" refers to the number of observations for each subgroup. The vertical line represents the null hypothesis [$ln(RR) = 0$]. The squares are the point estimate of effect size. The horizontal lines are the associated 95% confidence interval for the population parameter.

Under different irrigation management, it seems that RT and NT tillage regimes led to higher productivity than CT (on average 2.4, 4.3, and 6.9 in NT, RT, and CT, respectively), especially when organic fertilizers were applied in combination with mineral fertilizer (Figure 7). Additional water supplied through irrigation enhanced plant N uptake, especially under conservation than conventional tillage systems [68]. It also highlights that additional water supply could be a good strategy when depending on MO under conservation tillage practices.

4. Conclusions

This study highlights how fertilizer management and tillage regime may determine important impacts on soil health and productivity. The findings showed that the soil organic carbon and crop yield response varied due to climate conditions, soil properties, crop species, and water management. This study showed that some agronomical practices such as conservation tillage, especially zero or no-tillage (NT), and organic fertilization that are widely promoted for their agro-ecological benefits do not always lead to productive agroecosystems, therefore their adoption should be motivated by the effective benefits that may bring in specific agro-environmental conditions. In addition, the results highlighted the importance of the environmental and agronomical factors that need to be evaluated for a specific situation, and how their understanding could affect the impact of these farming practices on crop productivity and the sustainability of the agroecosystems in a specific region.

This study highlighted:

1. Climate conditions have more influence on crop yield when depending on organic sources alone, than combining both organic and inorganic fertilizers, both in comparison with inorganic sources alone.
2. Crop yields of O alone compared with M were more affected by climate and tillage system in humid conditions.
3. Application of organic nutrient sources alone (O) under an RT system could produce higher grains than the M fertilizers for legume crops.
4. Combining both inorganic and organic fertilizers (MO) under an RT system could produce higher grains for cereal crops.
5. Adopting MO fertilizers under RT practice added significant benefits in sandy soils.

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