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Yield gap between organic and conventional farming systems across climate types and sub-types: A meta-analysis

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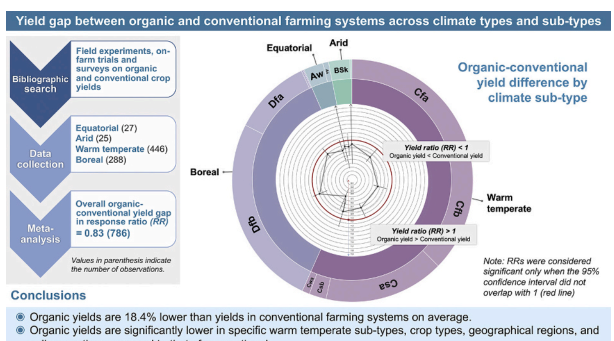
HIGHLIGHTS

- Yield of organic farming is 18.4% lower than that of conventional farming.
- Yield of organic farming is lower in specific warm temperate sub-types, crop types, geographical regions, and soils.
- Variations in organic-conventional yield ratio due to temperature and precipitation are difficult to estimate.

GRAPHICAL ABSTRACT



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ABSTRACT

Context: Organic farming is a fast-growing system considered a holistic approach that benefits the environment. However, previous studies have reported varying results on its productivity when compared to conventional farming systems. Moreover, the effect of climatic conditions on the yield gap between organic and conventional methods has not been extensively studied.
Objectives: Considering the influence of temperature and precipitation on soil microbial activity that drives the decomposition of organic matter and supports the mineralization of organic matter for plants, we hypothesized that the yield gap between organic and conventional farming systems is affected by climatic conditions; that is, it should be higher in locations with warmer climates that those in colder climates.
Methods: Yield data were collected from 105 studies that compared organic and conventional farming; 786 pairwise observations were extracted mainly from previous meta-analyses and individual studies. Using meta-analysis in R software, we examined the yield ratio between the two farming systems in different climate types (boreal, warm temperate, arid, and equatorial) and sub-types, and further investigated other influencing factors such as crop type, study location by region, and soil pH and texture.
Results and conclusions: The yield of organic farming was 18.4% ($RR = 0.83$; 95% confidence interval of 0.77 to 0.89; $p = < 0.0001$) lower than that of conventional farming, regardless of climate condition, crop type, and other categorical variables. Results showed that only the warm temperate climate had a significant effect on the yield gap between organic and conventional farming systems, where organic yields were 21.18% lower than

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those of conventional farming ($RR = 0.79$; 95% CI 0.71 to 0.87; $p = < 0.0001$; $k = 446$). However, the variability associated with temperature and precipitation was difficult to estimate using the current data. Among the categorical variables evaluated, it was found that specific crop types, regions, and soils significantly influenced the yield gap. Additional analyses revealed a confounding crop-type effect on the yield gap that requires further investigation. Nevertheless, this study suggests that when determining variations in the yields and productivity of organic and conventional farming systems, it is critical to account for interactions between variables.

Significance: The results of this study offer a preliminary understanding of how the climate type affects the yield of the two farming systems in a particular geographic location, supporting future research that will provide a quantitative context to land use development for sustainable agriculture.

1. Introduction

Organic agriculture has been a fast-growing farming system since the year 2000 in terms of global and regional production areas and percent land share (Willer et al., 2022). According to the 2022 report of the Research Institute of Organic Agriculture (Forschungsinstitut für Biologischen Landbau, FiBL), 74.9 million hectares of land were used for organic farming as of 2020 (equivalent to 1.6% of the global total agricultural land), including areas in-conversion (Willer et al., 2022).

Organic agriculture, referred to as "organic farming" hereafter, is a holistic production system that emphasizes the use of management practices, such as off-farm inputs based on site-specific needs and locally adapted systems (Joint FAO/WHO Codex Alimentarius Commission, 2007). Furthermore, it eliminates the use of synthetics inputs (Shennan et al., 2017). As an alternative farming system for sustainable agriculture, the primary aim of organic farming is to promote and enhance agroecosystem health, including biodiversity, biological cycles, and soil biological activity (Joint FAO/WHO Codex Alimentarius Commission, 2007).

In contrast, from the perspective of organic standards, particularly those of the International Federation of Organic Agriculture Movements (IFOAM) (2014), the word "conventional" is defined as any material, production, or processing practice that is not organic or organic "in conversion." Therefore, conventional agriculture is described as a farming system where synthetic pesticides, herbicides, and fertilizers are typically used. Furthermore, fields are frequently planned with short crop rotation cycles (Shennan et al., 2017). In such scenarios, relying on the intensive application of mineral fertilizers has contributed to the loss of soil organic carbon, environmental pollution, loss of biodiversity, and adverse climate change (Allam et al., 2022; Martini et al., 2004). Therefore, these environmental issues caused by the industrialization of agriculture have created the necessity of ecological farming practices. Organic farming is a widely adopted system based on sustainable agriculture (Allam et al., 2022). Furthermore, as organic farming reduced the clearing of primary ecosystems (El-Hage Scialabba and Müller-Lindenlauf, 2010) and use of inputs, and increased carbon sequestration, it contributed to lowering greenhouse gas emissions (Smith et al., 2019b).

The environmental benefits of organic farming and its specific management practices have been studied extensively and validated through cohorts and meta-analyses. Organic farms have 7% higher soil organic matter concentration (Tuomisto et al., 2012) and approximately 34% higher biodiversity (species richness) (Tuck et al., 2014) compared to conventional farms. Furthermore, organic systems had 32–84% greater microbial biomass carbon, microbial biomass nitrogen, and total phospholipid fatty acids, as well as greater dehydrogenase, urease, and protease activities, compared to conventional systems (Lori et al., 2017). Moreover, organic farming can apply strategies to mitigate the emergencies brought about by global warming (Cidón et al., 2021); for instance, it exhibits lower nutrient losses and energy requirements (Tuomisto et al., 2012). Tuomisto et al. (2012) conducted a meta-analysis and reported that organic systems exhibited 31 and 18% lower nitrous oxide and ammonia emissions per unit of area, respectively, as well as 1% lower phosphorus losses, and 21% lower energy consumption, compared with conventional systems.

The application of organic manure, a common input in organic farming, was recently reported to facilitate the improvement of soil water-nutrient status, thereby promoting sustainable soil and productivity in maize, as well as friendly soil environmental management in dryland farming, particularly in alkaline soils (Wang et al., 2020). In a more recent study on cacao production in a tropical humid climate with dry winters, organic management enhanced the chemical and biological soil quality and taxonomically diverse soil fungal and bacterial communities compared to conventionally managed systems (Lori et al., 2022).

The productivity of organic farming systems and their capacity to address the global food demand of a rapidly increasing population has been debated. Its popularity has amplified among consumers and the progressive global market (Badgley, 2007; Halberg et al., 2005; Trewavas, 2001; Stanhill, 1990). Incidentally, the claimed benefits of organic farming have been contested by Stanhill (1990) and Trewavas (2001), who criticized that organic farming produces lower yield and requires more production area to generate the same amount of food as conventional farms, further exacerbating deforestation and biodiversity loss, thus diminishing its environmental benefits. In addition, Smith et al. (2019a) conducted a meta-analysis and suggested the presence of an apparent trade-off in yield variability despite the improved stability of ecosystem services provided by organic farming. Conversely, yield variability can be decreased in conventional farms by the increased capability of readily adapting to environmental pressures via the abundant pesticide and fertilizer options. In addition, they reported that organic and conventional farming produced "win-win" opportunities in terms of biological communities and production, respectively.

In one of the early meta-analyses that compared the yields of the two farming systems, Seufert et al. (2012) reported lower yields from organic farming than those from conventional farming. Furthermore, it emphasized that differences in yield are highly contextual to system and site characteristics. Notably, they reported 5% lower yields in organic compared to conventional systems in rain-fed legumes and perennials on weak-acidic to weak-alkaline soils, 13% lower yields when best organic practices were applied, and 34% lower yields when the two farming systems were most comparable. They also observed that nitrogen (N) availability was a major yield-limiting factor in organic systems. This comparative study on yield was subsequently followed by a meta-analysis conducted by Knapp and van der Heijden (2018), who reported a 15% reduction in temporal yield stability in organic farming compared to that of conventional farming.

Among the meta-analyses reviewed in this study, it was observed that the effect of different climatic conditions received less attention when evaluating the yield gap between organic and conventional farming systems. Indeed, crop growth is affected by climatic conditions, including temperature (Kaspar and Bland, 1992; Rötter and Van De Geijn, 1999), precipitation, and humidity (Rötter and Van De Geijn, 1999), as well as by soil microbial diversity, abundance, and activity that facilitate nutrient availability through mineralization (Lopes et al., 2021; Sabri et al., 2018); however, the varying levels of temperature and precipitation may be factors that affect organic farming productivity.

Climate types have been observed to affect microbial activities (Lori et al., 2017). Furthermore, climate types have been linked explicitly to the temperature sensitivity of microbial communities. For instance, in organic farming at low temperatures, the mineralization of soil organic carbon, fresh organic matter, and microbial biomass were higher in tropical soils than in temperate areas (Santos et al., 2012). Consequently, the influence of different climate types on organic farming productivity warrants further study.

Therefore, this study focused on contextualizing the link between climate types and the gap in the yield of organic and conventional farming systems through a meta-analytical approach. The four climate types, i.e., boreal, warm temperate, arid, and equatorial, included in this meta-analysis are based on the Köppen-Geiger climate classification (KCC). The KCC differentiated these types by mean annual and monthly averages of temperature and precipitation regimes.

Considering the influence of temperature and precipitation on soil microbial activity, which determines the decomposition of organic matter and supports the mineralization of the nutrients unavailable for plant uptake, we hypothesized that: (1) the yield gap between organic and conventional farming systems is significantly affected by climatic conditions and (2) organic-farming yields are higher in locations with warmer climates than in those with colder climates.

This study aimed to understand the effect of different climatic conditions based on geographic locations on the yield gap of the two farming systems, serving as support and precedent to previous and future studies, respectively. Furthermore, the results of this study aim to supplement data-based helpful information for land use development and sustainable agriculture.

2. Materials and methods

2.1. Data collection

2.1.1. Bibliometric analysis

Data were first classified into two types: Type 1, data selected from previous meta-analyses (Badgley (2007) and Ponisio et al. (2015)); and Type 2, data extracted from an extensive bibliographic search.

For Type 2 data, a bibliographical search was conducted using the following Boolean keyword set: *(Title)* yield AND *(Title)* organic NEAR (system OR farm * OR agri * OR production) OR *(Title)* conventional NEAR (system OR farm * OR agri * OR production) in the Web of Science (https://www.webofscience.com/wos) accessed on February 16, 2022. The search was further filtered to include studies published from 2000 to 2022 (cut-off on February 16, 2022) in the English language, which resulted in 1411 publications. Subsequently, full-text copies were downloaded from EndNote (Version 20.1; USC-2101; 2020 Clarivate Analytics), ResearchGate (https://www.researchgate.net/), and personal correspondence.

We used the Preferred Reporting Items for Systematic Reviews and Meta-Analyses diagram to further select studies for Type 2 data (Fig. 1). The initial screening process involved two stages (Stage 1: Initial publication screening; Stage 2: Study selection pre-data extraction), which only differed on the selection criteria applied. The selection criteria were based on the criteria established by Seufert et al. (2012), Ponisio et al. (2015), and Knapp and van der Heijden (2018), and thereafter modified to fit the present study. The criteria included: (1) studies that reported comparable yield data for both organic and conventional farming systems were included; (2) irrelevant studies (i.e., not related to productivity in terms of yield) were excluded; (3) studies with data on non-food

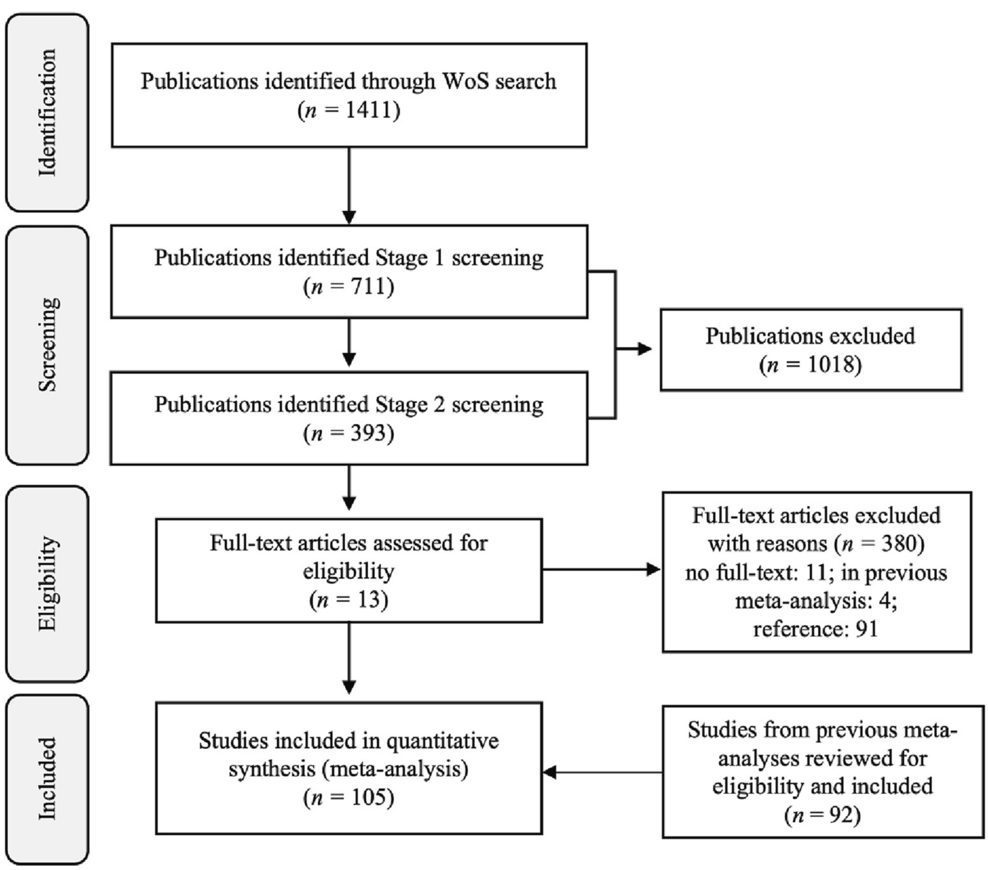

Fig. 1. Systemic review for data collection following Preferred Reporting Items for Systematic reviews and Meta-Analyses diagram for the selection of articles. Note: Screening was performed in two stages based on the selection criteria established—Stage 1: Initial publication screening, and Stage 2: Study selection pre-data extraction.

crops, livestock, and fisheries were excluded; (4) studies that have been peer-reviewed and published in journals, and grey literature with good study quality were included; (5) studies with data from the same publication in multiple databases were excluded; (6) studies with yield data in units that could not be transformed to tons ha^{-1} (i.e., lb. $plant^{-1}$, boxes ha^{-1}, kg $plant^{-1}$, g $plant^{-1}$, bales ha^{-1}, trays ha^{-1}, g $tree^{-1}$, kg $tree^{-1}$) were excluded; (7) studies that did not report a comparable mean, sample size, and standard deviation/error were excluded; and (8) studies that only reported log-transformed values, pooled values, and yield ratios were excluded. Here, we considered the yield data to be comparable if they were generated under the same study; hence, the treatments followed a similar experimental design, conducted in the same spatial scale, and utilized the same crop species. Finally, studies included in previous meta-analytical studies (Type 1 data) were thoroughly assessed and integrated as the final step of data collection (Fig. 1). Specifically, the data from the original datasets of Badgley (2007) and Ponisio et al. (2015) were selected and further processed. Given that this study relied heavily on the mentioned datasets (mainly on Ponisio et al. (2015)) for Type 1 data, it should be noted that only 13 new studies (705 observations) were added.

The categorical variables were classified as follows: (1) climate types were divided into four categories—equatorial, arid, warm temperate and boreal; (2) climate sub-types into thirteen categories based on the Köppen-Geiger Climate Classification system; (3) crop types into eight categories—fruits and nuts, vegetables and melons, oilseed crops and oleaginous fruits, cereals, sugar crops, leguminous crops, root/tuber crops, and stimulant, spice and aromatic crops; (4) geographical regions into North America, Asia, Europe, NZ-Australia, Africa, and South America; (5) soil pH into three categories—strong acidic, weak acidic to weak alkaline, and strong alkaline; and (6) soil textural class into seven categories—clay loam, sandy clay, loamy sand, silty clay loam, loam, sandy loam, and silt loam.

2.1.2. Data extraction, transposition, and imputation

Comparable means, sample sizes, and standard deviations from the selected studies were extracted. In total, 105 studies involving 786 observations were obtained after combining Type 1 and 2 data. The included studies presented multiple observations that used single or multiple test crops and multiple study locations in some cases. Therefore, pairwise observations (comprising values for both organic and conventional treatments) were treated and weighed as individual samples (k).

With respect to missing climatic data, the specific climatic classes of study locations were identified by Google Earth Pro (Version 7.3.4.8573; 64-bit) using the 1986–2010 Köppen–Geiger climate classification map (.kml) layer (Resolution 5 arc minutes; Version 18.03.2017; Source: koeppen-geiger.vu-wien.ac.at). Before the effect size computation, yield data using tons per hectare were retained, and those in other units were converted to tons per hectare. The list of studies included in the meta-analysis is provided in Supplementary Information 1.

2.2. Effect sizes and meta-analytic model

The random effects model (multivariate meta-analysis) was used as appropriate for the continuous data type and to account for the dependence of effect sizes from the same study (Viechtbauer, 2010). The natural log of response ratios (*lnRR*) between organic and conventional farming systems was selected as the effect size to measure the yield gap as it was used in previous meta-analyses (Seufert et al., 2012; Badgley and Perfecto, 2007; Ponisio et al., 2015; and Smith et al., 2019a) and experimental ecology in general (Hedges et al., 1999; Lajeunesse, 2011). The *lnRR* is mathematically expressed as: $lnRR = ln(\overline{X}_E/\overline{X}_C)$, where lnRR is the natural-log proportional change in the means ($\overline{X}$) of the organic (E) and control group (C) (Lajeunesse, 2011).

For interpretation purposes, an effect size was considered statistically significant if its 95% confidence interval did not overlap with 1 in the back-transformed response ratio, where $RR = \exp.(lnRR)$. $RR < 1$ indicates that yield in organic farming systems is lower than that of conventional farming systems as influenced by the climate type or subtype, as well as by other factors under investigation. On the contrary, an $RR > 1$ indicates a higher yield in the organic treatment than in the control group as influenced by a respective categorical variable.

2.3. Meta-analysis

Statistical computations were performed using the R software version 4.2.2 (2022-10-31; aarch64-apple-darwin20 (64-bit)). The "metafor" version 3.8–1 (Meta-Analysis Package for R) package was used to process the dataset for this meta-analysis.

After the dataset was loaded in R, individual natural log response ratios and standard errors were computed and then nested within studies using the R packages "dplyr" version 1.1.2 (A Grammar of Data Manipulation) and "tidyr" version 1.3.0 (Tidy Messy Data) to avoid pseudo-replication and Type 1 error (Lajeunesse, 2011). The expanded traditional hierarchical meta-analysis, as implemented by Ponisio et al. (2015), was performed, including the addition of two random effects (between and within study variations) to potentially decrease heterogeneity.

A random effects model (multivariate meta-analysis) was fitted to account for the non-independence in the effect sizes (Viechtbauer, 2010). Estimates of variance components, effect sizes, reference level of intercepts, estimated coefficients for each categorical variable, and measures of heterogeneity were computed. In this study, the estimated coefficients represent the expected change in the organic-conventional yield ratio relative to the reference level of the intercept, holding all other predictors constant. Subsequently, prediction intervals were computed. Effect sizes were then back-transformed to their original scale and plotted in forest plots.

Between-study variances (τ^2) were also computed to understand and characterize the variations in the data. The Restricted Maximum Likelihood (REML) method was applied as a τ^2 estimator. A mixed effects meta-regression model was also fitted to test the relationship between yield ratio and each categorical variable, as well as the interactions between climate categorical variables and other categorical variables, such as crop type, soil pH and texture, and study location by region. The results of these tests are presented in Supplementary Information (SI) 5.

3. Results

3.1. General data evaluation

The data included were distributed among four climate types: boreal, warm temperate, arid, and equatorial. The Köppen–Geiger climate classification characterizes these groups by their mean annual and monthly averages of temperature and precipitation regimes. Belda et al. (2014) and Peel et al. (2007) further characterized these climate types, as seen in Table 1.

The data show that most boreal studies were conducted in Europe and North America. The warm temperate climate type (*C*) was found in the two previously mentioned regions, including some countries in Asia and Africa, located near the Arctic region, while the arid climate group (*B*) was the least represented climate type in the dataset. Lastly, studies in equatorial areas were conducted in Asia and South America (SI 7.3).

In terms of the geographical distribution of the included studies (i.e., observations), the largest number of observations was extracted from studies conducted in North America (44%, $k = 347$) and Europe (42%, $k = 320$) (SI 2.6). Furthermore, in these studies, the most utilized test crops were cereals (i.e., maize, wheat, barley, oats, and rye), accounting for 53% ($k = 419$) of the crop groups used (SI 2.4.b, SI 2.5). Even when most observations were collected from studies in North America and Europe, the heterogeneity was also the highest in these subgroups. The

Table 1
Summarized characteristics of climate types by Belda et al., 2014 and Peel et al., 2007. Function T refers to the mean annual temperature in °C.

Climate type	Code	Description
Equatorial	*A*	• Average temperature in cold months is higher than 18 °C • Mean precipitation is generally greater than that of arid zones and less than or higher than 60 mm during dry months.
Arid	*B*	• Maximum precipitation is less than 20 mm x T + 280 in summer and a mean of less than 20 mm x T in winter. • Annual rainfall averages in less than 20 mm x T + 140 mm.
Warm temperate	*C*	• Average temperature in cold months ranges from 18 to −3 °C and in warm months is higher than 10 °C. • Mean precipitation similar to that of boreal climates
Boreal	*D*	• Average temperature in cold months is lower than −3 °C and in warm months is higher than 10 °C. • Mean annual precipitation is less than 890 mm and greater than that of the arid rainfall range. • Likelihood of no dry season in fully humid (*Df*) areas

remaining fraction of the data comprised observations from Asia (k = 96, 12%), Africa (k = 12, 2%), New Zealand (NZ)-Australia (k = 7, 1%), and South America (k = 4, 1%). A summary of the information of the included studies is presented in SI 2.

According to the overall heterogeneity test (SI 5) results, a significant quantified variance of the distribution of effect sizes, τ^2, is equal to 0.1639 (SE = 0.0094). These results suggest that the variability among the effect sizes can be attributed to differences in the measured effect sizes (Higgins et al., 2022).

3.2. Overall yield gap

The overall yield gap, as expressed in the organic-conventional yield ratio, indicated that yields were significantly lower in organic farming than in conventional farming (Fig. 2). Results of this meta-analysis showed that the overall organic-conventional yield ratio was 0.83 (with a 95% CI of 0.77 to 0.89, p-value <0.0001) or an average of 18.4% lower organic yields, regardless of the effects of categorical variables, such as climate, crop type, geographical location, and soil pH and textural class factored in. However, results also suggest that the influence of climate type and sub-type, study location, and soil texture on the yield gap is not statistically significant. The computed prediction interval indicates that future effect sizes (in RR) are expected to fall within the range of 0.35 to 1.97 (Fig. 2). Notwithstanding, the wide prediction interval suggests a high level of heterogeneity in the meta-analysis; therefore, it is less informative.

3.3. Yield gap by climatic conditions, crop type, study location, and selected soil characteristics

The yields of organic farming were generally lower than those of conventional farming across climate types without considering the significance levels of each subgroup. However, the result of this analysis suggests that only the warm temperate climate type has a significant effect on the yield gap between organic and conventional farming systems, and that organic yields are 21.18% lower (RR = 0.79; 95% CI 0.71 to 0.87; $p \leq$ 0.0001; k = 446). Albeit yield ratios in boreal, arid, and equatorial climates are higher than the effect size of warm temperate and the general inference (or the overall yield gap), levels of statistical significance imply this finding is inconclusive (Fig. 3).

As it is difficult to contextualize these outcomes solely based on the climatic conditions of the four climate types, as three were not statistically inferable, subgroup analyses for (1) the Köppen–Geiger climate sub-type, (2) study crop type (group), (3) study location (region), and (4) soil pH and texture were conducted to detect the possible effects on productivity variations.

Figs. 3 and 4 show no specific pattern (increasing or decreasing) in the yield ratios between climate types and subtypes. In the subgroup analysis for climate sub-type (Fig. 4), significantly lower yield ratios were observed in four warm temperate subtypes, and these were ranked (from highest yield ratio) as follows: Warm temperate with dry and hot summer (*Csa*) (17.54% lower yields in organic; RR = 0.82; 95% CI 0.69 to 0.98; p = 0.0319; k = 131) > Warm temperate, fully humid with hot summer (*Cfa*) (17.61% lower yields in organic; RR = 0.82; 95% CI 0.66 to 1.02; p = 0.0805; k = 163) > Warm temperate, fully humid with warm summer (*Cfb*) (24.20% lower yields in organic; RR = 0.76; 95% CI 0.63 to 0.92; p = 0.0045; k = 126) > Warm temperate with dry winter and hot summer (*Cwa*) (48.88% lower yields in organic; RR = 0.51; 95% CI 0.33 to 0.78; p = 0.0020; k = 18). *Csa, Cfa, Cfb,* and *Cwa* were also observed to be in the lower half of the overall ranking for climate subtypes. On the contrary, the following subtypes exhibited no significant effect on organic-conventional yield ratio: Equatorial savannah with dry summer (*As*) and with dry winter (*Aw*), Desert, hot (*BWh*), Steppe, cold (*BSk*), warm temperate with dry and warm summer (*Csb*), Boreal, fully humid with hot summer (*Dfa*), Boreal, fully humid with warm summer (*Dfb*), Boreal with dry winter and hot summer (*Dwa*), and Boreal with

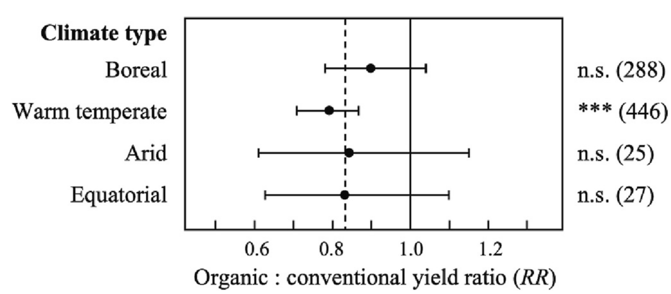

Fig. 3. Organic-conventional yield ratio (response ratio) of the four climate types in the Köppen–Geiger Climate classification system (boreal, warm temperate, arid, and equatorial). The horizontal line indicates a 95% confidence interval of the effect size. Response ratios were considered significant only when the 95% CI did not overlap with 1. The vertical broken line indicates the average effect size across all categories. Values enclosed in parentheses () denote the number of observations for each subgroup. "***" and "n.s." refer to the p-value at 0 and not statistically significant, respectively.

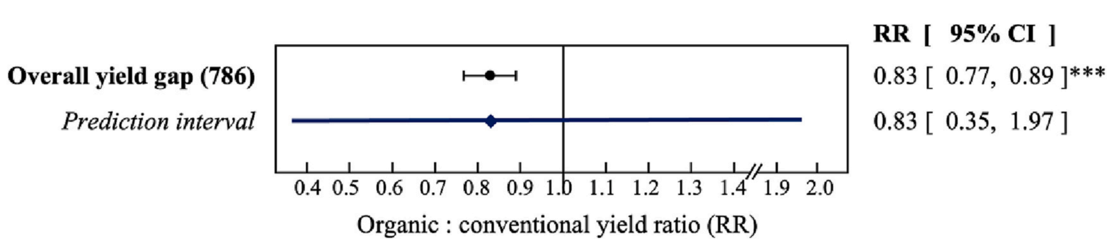

Fig. 2. Organic-conventional yield ratios (back-transformed response ratio) at n = 786. The horizontal line indicates a 95% confidence interval of the effect size. An effect size with a 95% CI overlapping the value of 1 is considered not statistically significant. The value enclosed in parentheses () denotes the number of observations. "***" refers to the p-value at 0.

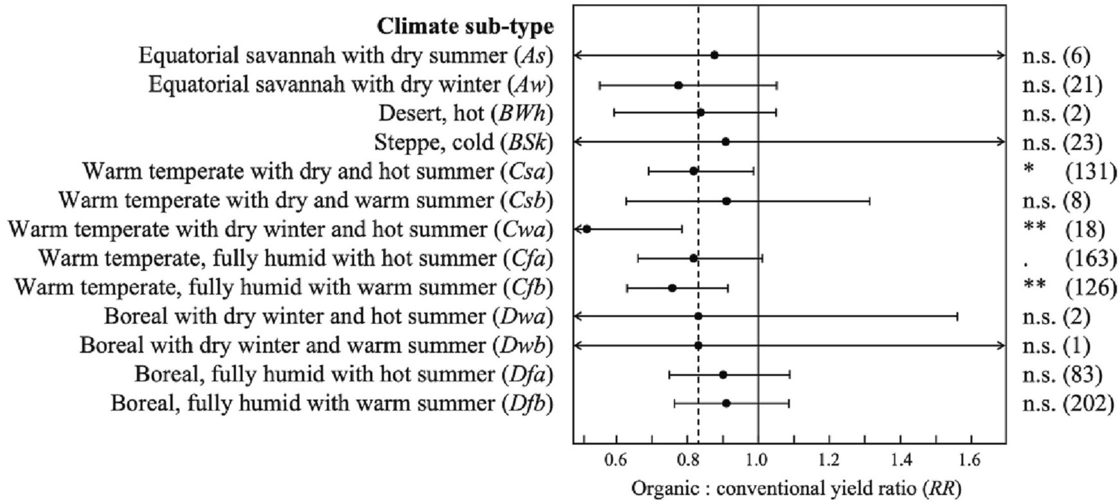

Fig. 4. Organic-conventional yield ratio (response ratio) across the climate sub-types based on Köppen–Geiger Climate classification system. Sub-type description: Equatorial savannah with dry summer (*As*) and dry winter (*Aw*); Desert, hot (*BWh*); Steppe, cold (*BSk*); Warm temperate with dry and hot summer (*Csa*) and warm summer (*Csb*); Warm temperate with dry winter and hot summer (*Cwa*); Warm temperate, fully humid with hot summer (*Cfa*) and warm summer (*Cfb*); Boreal with dry winter and hot summer (*Dwa*) and warm summer (*Dwb*); Boreal, fully humid with hot summer (*Dfa*) and warm summer (*Dfb*). The horizontal line indicates a 95% confidence interval of the effect size. Response ratios were considered significant only when the 95% CI did not overlap with 1. The vertical broken line indicates the average effect size across all categories. Values enclosed in parentheses () denote the number of observations for each subgroup. "**," "*," ".," and "n.s." refer to the p-value at 0.001, 0.01, 0.05, and not statistically significant, respectively.

dry winter and warm summer (*Dwb*). The *p*-values across all sub-types indicate no statistical significance. Therefore, a concrete general inference on this subgroup was not drawn.

Climate subtypes under the warm temperate climate type (*C*) showed more scattered values across the <1 spectrum compared to those of the equatorial (*A*), arid (*B*), and boreal (*D*) types. Likewise, effect sizes of equatorial and arid subtypes follow no particular pattern in general and in reference to the overall yield gap value, whereas similar effect sizes were observed between similar subtypes in the boreal front. For example, the effect sizes were almost identical between fully humid (*Dfa* and *Dfb*) boreal subtypes.

In the categorical analysis of crops (Fig. 5), most crop types showed lower yields in organic farming than in conventional farming. The highest yield ratio was noted for fruits and nuts ($RR = 1.02$; 95% CI 0.75 to 1.39; $p = 0.8847$; $k = 25$). However, this group, represented by apples, grapes, hazelnut, and strawberry, was noted to have no statistical significance. Significantly lower yields in organic farming were observed in vegetables and melons ($RR = 0.85$; 95% CI 0.76–0.95; $p = 0.0041$; $k = 172$), oilseed crops and oleaginous fruits ($RR = 0.84$; 95% CI 0.76–0.94; $p = 0.0016$; $k = 105$), cereals ($RR = 0.82$; 95% CI 0.76–0.90; $p \leq 0.0001$; $k = 419$), leguminous crops ($RR = 0.75$; 95% CI 0.62–0.90; $p = 0.0018$; $k = 20$), root/tuber crops ($RR = 0.71$; 95% CI 0.60–0.85; $p = 0.0002$; $k = 38$), and ranked the lowest were stimulant, spice and aromatic crops ($RR = 0.49$; 95% CI 0.26–0.92; $p = 0.0272$; $k = 3$). The vegetables and melons included in this meta-analysis were mainly tomatoes, cauliflower, lettuce, and spinach; oilseed crops and oleaginous fruits were mainly soybean; the cereal group comprised maize, wheat, barley, and oats; leguminous crops were beans, pigeon peas, and cowpeas; and root/tuber crops were potato, sweet potato, and elephant foot yam (SI 2.4 b, 2.5). Yield ratios of sugar crops ($RR = 0.79$; 95% CI 0.37–1.69; $p = 0.5397$; $k = 4$) were statistically non-significant as their 95% CI overlapped the value 1.

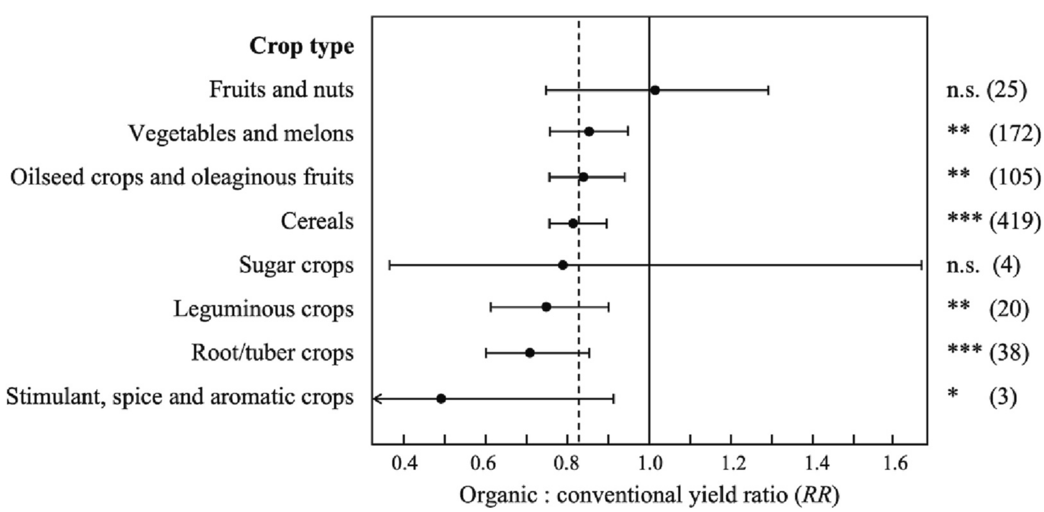

Fig. 5. Organic-conventional yield ratio (response ratio) of different crop types with a 95% confidence interval (CI). Response ratios were considered significant only when the 95% CI did not overlap with 1. The vertical broken line indicates the average effect size across all categories. Values enclosed in parentheses () denote the number of observations. "***," "**," "*," and "n.s." refer to *p*-value at 0, 0.001, 0.01, and not statistically significant, respectively.

Considering the statistical significance of several crop types (Fig. 5), we further investigated the influence of crop type alone and the interaction between climate type and crop type on the yield ratios of organic and conventional farming systems using meta-regression analyses (SI 6). The meta-regression results on crop type confirmed the results of the subgroup analysis (Fig. 5). The meta-regression analysis on the climate type-crop type interaction, especially considering the test of moderators (QM) where $p < 0.001$, revealed that the effect of the interaction between climate type and crop type on the yield ratios of organic and conventional farming systems were significantly related to crop yield. However, despite the significant effect in all climate types, only fruits and nuts, oilseed crops and oleaginous fruits, and root/tuber crops showed statistical significance among crop types. Notably, the analysis of this interaction resulted in significant positive estimates (higher organic yields) in the mentioned crop types. Whereas the crop types that had significant effect sizes in the related subgroup analysis and meta-regression except for oilseed crops and oleaginous fruits, and root/tuber crops (i.e., cereals, vegetables and melons, leguminous crops, and stimulant, spice and aromatic crops) showed no significant effect between organic and conventional yields. This result showed that when climate type is factored into the analysis, the influence of crop type drastically differs. Nonetheless, these varying results likely signify that crop type generally strongly influences the organic-conventional yield ratio. Interpreting the results for each crop type should be done cautiously.

Yield ratios by region (the lower resolution of the study location variable) were also measured using subgroup analysis (Fig. 6). Consistent with the findings of previous subgroup analyses on climatic conditions, yield ratios indicated lower yields from organic farming. Despite having the highest yield ratio and similarity with Europe in terms of standard error and large sample size, a statistically non-significant yield ratio was reported in North America ($RR = 0.92$; 95% CI 0.82–1.03; $p = 0.1508$; $k = 347$). Significantly lower yields in organic farming were reported in Asia ($RR = 0.82$; 95% CI 0.68–0.98; $p = 0.0320$; $k = 96$), Europe ($RR = 0.75$; 95% CI 0.66–0.86; $p \leq 0.0001$; $k = 320$), and South America ($RR = 0.52$; 95% CI 0.30–0.91; $p = 0.0215$; $k = 4$), equivalent to 18.06%, 24.83%, and 47.73%, respectively. Whereas, similar to that in North America, no significant effect on yield ratio was found in NZ-Australia ($RR = 0.92$; 95% CI 0.82–1.03; $p = 0.2909$; $k = 347$) and Africa ($RR = 0.92$; 95% CI 0.82–1.03; $p = 0.2051$; $k = 347$) due to its widely distributed effect sizes. Hence, inferences were not drawn for the three latter regions.

Finally, we investigated the possible effects of selected soil characteristics reported by individual studies, such as soil pH and textural classes (Fig. 7). The results showed a significant effect in weak acidic and weak alkaline ($RR = 0.86$; 95% CI 0.78–0.96; $p = 0.0054$; $k = 423$) and strong alkaline ($RR = 0.65$; 95% CI 0.50–0.85; $p = 0.0014$; $k = 38$) soils. These values indicate a lower yield ratio in organic farming by 13.8% and 35.1%, respectively. Regarding the rest of the soil pH levels evaluated, such as strong acidic ($RR = 0.88$; 95% CI 0.74–1.05; $p = 0.14494$; $k = 68$), the outcome exhibited no significant influence on the yield ratio of the two farming systems. In addition to this probing on soil pH-yield ratio interaction, the subgroup analysis on soil textural classes also revealed a significant effect in sandy loam soil ($RR = 0.86$; 95% CI 0.78–0.96; $p = 0.0054$; $k = 423$), with 27.6% lower yields in organic than that in conventional farming. The rest of the classes indicated no significant effect on the yield ratio. Moreover, it was observed that the mean effect sizes in sandy clay ($RR = 1.19$; 95% CI 0.62–2.29; $p = 0.5971$; $k = 5$) and loamy sand ($RR = 1.07$; 95% CI 0.76–1.50; $p = 0.7066$; $k = 20$) possess values greater than 1, demonstrating higher organic yields in studies that utilized soils with such textures. Nonetheless, this finding is rather uninformative due to its respective p-values.

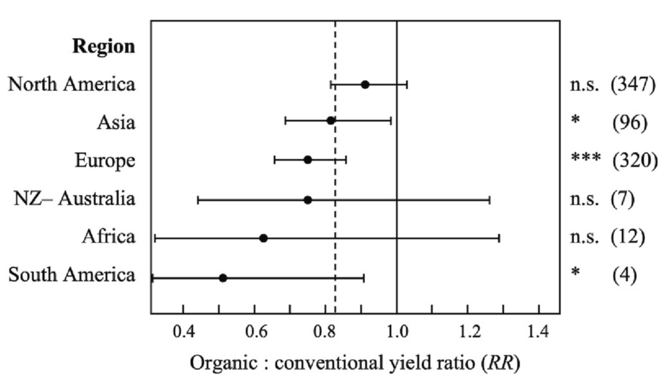

Fig. 6. Organic-conventional yield ratio (response ratio) in different regions with a 95% confidence interval (CI). Response ratios were considered significant only when the 95% CI did not overlap with 1. The vertical broken line indicates the average effect size across all categories. The value enclosed in parentheses () denotes the number of observations. "***," "**," "*," and "n.s." refer to p-value at 0, 0.01, and not statistically significant, respectively.

The horizontal line indicates a 95% confidence interval of the effect size. Response ratios were considered significant only when the 95% CI did not overlap with 1. The vertical broken line indicates the average effect size across all categories. Values enclosed in parentheses () denote the number of observations. "**," "*," and "n.s." refer to p-value at 0.001, 0.01, and not statistically significant, respectively.

4. Discussion

4.1. Lower yield in organic farming across categorical variables

The overall meta-analysis showed that the yield was significantly lower in organic farming than in conventional farming across all categorical variables evaluated in this study, specifically among climatic types and sub-types. Our results agree with the outcomes of previous meta-analyses on organic productivity (gap, stability, and variability) conducted by Seufert et al. (2012), de Ponti et al. (2012), Ponisio et al. (2015), Knapp and van der Heijden (2018), and Smith et al. (2019a). However, these studies differed in terms of the variables explored.

The present study further suggests that climatic conditions affect the yield gap between organic and conventional farming systems, particularly in warm temperate climate and its subtypes *Csa*, *Cwa*, *Cfa,* and *Cfb*. Consequently, having no significant reference to compare the warm temperate effect size and with the added perspective and dimension from the subgroup analyses, no association was made between the change in yield and the change in climatic conditions; hence, we have no solid basis for assuming a general causal relationship between the improvement in organic yield through the positive response of microbial activity and the changes in temperature and precipitation regimes. Therefore, we decided to refer to this association in previous studies based on the meta-analysis results.

The continued investigation through meta-regression warranted us to detect a confounding effect from the interaction between the climate type and crop type variables. It specifically directed us to the significant negative estimates for all climate types to support the general idea of our first hypothesis. Such finding emphasizes that a single-dimensioned (yield ratio-to-climate type/sub-type causal relationship) analysis is insufficient to understand the effect of climate on organic and conventional yield gaps, and that it is rather critical to account for the interactions between variables when assessing the yield gap between these two farming systems. Moreover, this study supports the findings of de Ponti et al. (2012), who reported that the gap between individual organic and conventional crop yields is highly contextual to the study location and crop group.

4.2. Association between climatic condition and yield

The results of this synthesis provided us with no solid basis for the

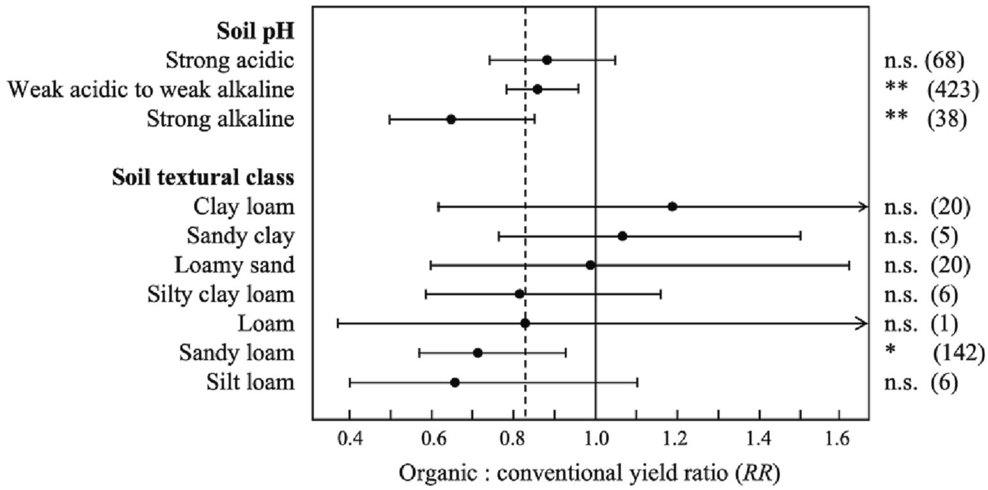

Fig. 7. Organic-conventional yield ratio (response ratio) across different soil pH and textural classes.

general causal relationship between organic yield increase and changes in temperature and precipitation; this consequently led us to reject our second hypothesis, which assumes that organic farming yields are higher in locations with warmer climates than in those with colder climates, thereby increasing the yield ratio. Given the characteristics of the four climate types, we initially expected the yield difference to follow the ranking equatorial > arid > warm temperate > boreal. Our results showed that colder climate types (warm temperate and boreal) result in higher yield ratios than do equatorial and arid zones.

The present study attempted to investigate the potential effects of climatic conditions on the yield ratio with microbial activity as the potential driver in improving the belowground condition for improved productivity in organic systems. However, without measures to perform the necessary analysis, we focused on other underlying factors such as crop types, geographical locations, and soil properties instead.

The results of the subgroup analysis for crop type showed a notable deviation from focusing on our hypothesis. Considering the significant effect sizes in crop types such as cereals and vegetables, and melons, which are over-represented in the warm temperate subset and the dataset per se, it is probable that the large yield difference between organic and conventional in said climate type (warm temperate) may be caused by a confounding effect of the crop type rather than climate type. Ponisio et al. (2015) explained that this excessive influence in cereal crops is likely due to its importance in the human diet and predominance in production areas, hence the great interest in research at a global scale.

Furthermore, the results on the yield-crop type and yield-crop type-climate type interactions suggest the strong influence of crop type on the yield ratio; however, the inconsistent response of specific crop types in these results requires further investigation on these interactions – provided the improvement in representations in the dataset.

4.3. Other factors affecting yield

Long-term studies showed that there were other factors that limit organic yields, thereby favoring the yields in conventionally treated production upon comparison. In sweet corn, the yield obtained through organic farming was less than 50% of that obtained through conventional methods because of the lack of available N and weed competition (Larsen et al., 2014). However, efficient management of catch crops effectively reduces N losses due to leaching to address the yield limitations caused by the dynamics of N in organic soils, specifically in organic cereals (Doltra et al., 2011).

Similarly, in a long-term experiment on corn and soybean yields, yield variability was affected by precipitation and temperature, specifically by precipitation and heat stress, during the early reproductive and late vegetative phases (Teasdale and Cavigelli, 2017). In this experiment, yields in corn and soybean were 31% and 20% lower in organic systems, respectively, than those in the corresponding conventional systems. Aronsson et al. (2007) reported 15–50% lower yield of cereals in organic systems than that in conventional systems, as affected by different management strategies in clay soil.

Various factors affecting organic productivity have been discussed in previous meta-analyses. As previously mentioned, de Ponti et al. (2012) specified that the gap between individual organic and conventional crop yields is highly contextual to the region and crop group. Generally, it is 80% on average. This meta-analysis was later supported by Ponisio et al. (2015), who reported a 19.2% lower yield in organic systems than that in conventional systems. Additionally, they concluded that multi-cropping and crop rotations could reduce the yield gap to 9±4% and 8±5%, respectively. Applying green manure and enhanced fertilization improved organic yield (Knapp and van der Heijden, 2018).

Finally, several studies have reported the benefits of organic farming practices in warmer climates and their prominent role in providing a better and more conducive environment for microbial communities that will, in turn, enhance organic yield. Improved yield in organic farming was associated with climatic conditions in equatorial areas, as it was reported in a previous meta-analysis that microbial communities in this climate type showed three times more dehydrogenase activity in soils under organic management than that in conventional soils due to temperature sensitivity (Lori et al., 2017). Microbial biomass in organic farming has also increased to a greater extent in tropical areas than in temperate areas (Santos et al., 2012). A recent meta-analysis concluded that organic farming systems improved soil ecological quality compared to conventional farming systems. Particularly, microorganism activity was strongly enhanced by 83%, and the abundance of microorganisms (fungal and bacterial) and soil fauna organisms by 75% in organic farming systems (Christel et al., 2021). Thus, organic farming systems are expected to consistently improve the overall soil biological properties that support growing conditions, especially plant nutrient uptake.

Despite having lower variability in biotic abundance and richness in organic farms, yield variability tends to be high (Smith et al., 2019a). However, this evidence is insufficient to conclude that warmer climates can support better soil microbial populations and activities, positively affecting organic yield. In addition, the scattered effect sizes in the subgroup analysis for climate subtypes could not substantiate this simple analogy. Likewise, the fluctuating yield ratios (relative to climate) in our meta-analysis do not provide conclusive evidence to support our second hypothesis.

5. Conclusions

This study suggests that the type of climate affects the yield ratio between organic and conventional farming. However, its variability in climatic conditions, specifically the relative change in temperature and precipitation, is challenging to estimate using the currently available data. Although not quantified in this study, the influence of other factors, such as specific crop species (plant life cycle, N-fixing abilities), management (system level, tillage, crop rotation, input application, amount, and type), and temporal dynamics, were considered to be embedded in the individual yield ratio estimates included in this study. The analysis of these variables was also not prioritized, as they have been sufficiently analyzed and contextualized in previous meta-analyses, including those by de Ponti et al. (2012), Seufert et al. (2012), Ponisio et al. (2015), Knapp and van der Heijden (2018), and Lori et al. (2017).

In addition to the limitation in the distribution of data among different climate and crop types, the limitation on the geographical distribution of data (in this case, high heterogeneity) also affected the significance of the subgroup analyses in this comparative study. Evidently, there is a need for better representation of arid and equatorial zones to strengthen the statistical power and regional representation of Africa and Asia, as these regions have three (arid, equatorial, and warm temperate) and five (all types) climate types, respectively (Peel et al., 2007). Moreover, future studies need to comprehensively explore the difference and updated Köppen–Geiger climate types, and utilize more site-specific climatic information (such as the use of actual temperature and precipitation data reported in primary) for higher precision, thereby providing a more in-depth understanding of organic productivity. Similarly, the confounding crop type effect should be further investigated in detail. However, a balanced data representation in crop types is critical to improve our understanding of their effect. This gap on the influence of crop types also emphasizes the importance of examining the correlation between yield and plant-nutrient dynamics of different crop types in response to organic treatments. This also implies that when determining variations in the yields and productivities of organic and conventional farms, it is critical to account for the interactions between variables, such as those mentioned above.

Finally, the meta-analysis is a powerful statistical tool that can provide a broad perspective on the productivity of organic farming systems and their implementation. Therefore, it can provide the context for future research endeavors and possibly to stakeholders involved in sustainable land use development initiatives. The present study was conducted to contribute to the knowledge of previous studies and potentially increase the scientific discourse on closing the gap between the yields of organic and conventional farming systems, especially in the context of climate change.

Declaration of Competing Interest

There is no conflict of interest.

Data availability

The dataset analyzed in this study is available upon request.

Acknowledgment

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2023.103732.

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