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Global synthesis of cover crop impacts on main crop yield

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ABSTRACT

Incorporating cover crops into farming systems represents a potential pathway to maintaining crop productivity and achieving multiple environmental benefits. However, how cover crops impact the succeeding crop yield remained a matter of debate. Therefore, this study aims to provide a comprehensive and global scale assessment of cover crop impacts on yield. We conducted a literature synthesis of cover crop studies (104 articles) to collect field-based yield data (1027 records) and used meta-analysis to quantify the impact of cover crops on subsequent main crop yields. Our results showed that cover cropping led to an overall moderate increase in main crop yield, amounting to 2.6%. Specifically, the utilization of leguminous cover crops, cultivation in coarse soil texture and dryland areas, and the implementation of longer cover cropping durations were found to be conducive scenarios to enhance crop yields. Conversely, the use of non-legume cover crops, introducing them to fields under a short-term no-till, especially in fine-textured soils, were impaired to yields. Leguminous cover crops showed the greatest potential for increasing yield (9.8%) particularly when paired with corn. Adopting leguminous cover crops without fertilizing main crops resulted in a 21.8% yield increase. Utilizing cover crops did not affect yield if the field had already under no-till practice. Introducing cover crops on coarser soils and in rainfed drylands can increase yield by 14.1% and 11.4%, respectively. In fine-textured soils, cover crop plus conventional tillage achieved 4.8% yield increase while cover crops plus no-tillage led to a 9.5% yield decrease instead. Consequently, our findings suggested the general yield profitability of cover crops, but substantial variations remain, which was primarily affected by availability of nitrogen and soil moisture. It is advisable to maximize the nitrogen-fixing capability of leguminous cover crops as a nitrogen source for main crops, replacing fertilizer. Particular attention should be paid, and additional management practices should be adopted when using cover crops plus no-tillage in fine-textured soils to avoid yield penalties. These specific supportive measures are suggested to shorten the lag period of yield increase within the initial 1–3 years of cover cropping implementation. Our synthesis quantified the overall cover crop impacts on yield, showcasing variable yield returns across different scenarios. This holistic understanding and comprehensive information can serve to advance the appropriate and targeted adoption of cover crops by policymakers, extension services, and farmers.

1. Introduction

High-yield aimed agriculture practices have caused and will continue to cause nitrogen (N) pollution (Daryanto et al., 2017; Abdalla et al., 2019), agroecosystem biodiversity loss (Guerrero-Pineda et al., 2022), soil degradation (Muhammad et al., 2021), pesticide pollution (Elias et al., 2018; Larsen et al., 2021), more greenhouse gas emissions (Crippa et al., 2021; Laborde et al., 2021), and other environmental issues (West et al., 2014; Balmford et al., 2018). With the substantial environmental costs of modern agriculture practices, a more climate-resilient and sustainable food production system is called for to meet increasing food demand and cope with environmental sustainability (Hunter et al., 2017; Poore and Nemecek, 2018; Pretty et al., 2018; Jastrzębska et al., 2022).

Planting cover crops is a potential choice to reduce the environmental burden (Blanco-Canqui et al., 2015; Afshar et al., 2018; Daryanto et al., 2018) while maintaining crop productivity (Tonitto et al., 2006). Cover crops are plants typically cultivated between income-producing crops to cover the soil surface following the harvest of the main grain crops. It has been recognized as aa beneficial practice that provides various advantages, such as enhancing soil physical and microbial properties (Blanco-Canqui and Ruis, 2020), soil erosion control (Liu

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et al., 2021; Saba and Christy, 2021), N leaching (Gabriel et al., 2013; Thapa et al., 2018), soil organic carbon sequestration (Jian et al., 2020), weeds suppression (Koehler-Cole et al., 2017; Monteiro et al., 2021), and greenhouse gas fluxes (Quemada et al., 2020; McClelland et al., 2021; Li et al., 2023). Despite having several agro-environmental advantages, cover crops are perceived by farmers as a long-term investment that can hardly pay for themselves quickly (DeVincentis et al., 2020), especially considering that cover crops might potentially reduce the yield of main crops (Bergtold et al., 2019). Therefore, at the farm operation level, planting cover crops remains an underutilized strategy. USDA Census Data has shown that cover cropping accounted for less than 5% of all U.S. agriculture in 2017 (USDA, 2017; Zulauf and Brown, 2019). In the European Union, more than 23% of arable land was still left without cover crops during the winter of 2016 (Bellassen et al., 2022), despite the mandatory arable land maintenance Common Agricultural Policy.

To promote the environmental benefits of cover crops, various public subsidies, such as the Pandemic Cover Crop Program (PCCP), have been implemented to encourage farmers to adopt cover crops (Mercier and Halbrook, 2020). These subsidies are largely allocated based on the cost of seeds, equipment, and labor involved in cover cropping, and assume no change in the yield of the main crop, which is not always consistent with field observations (Zulauf and Schnitkey, 2022). Quantitatively determining whether cover crops increase or decrease main crop yield provides additional assurance to producers concerned about yield losses, as well as the data needed by policymakers to more accurately estimate cover crop insurance subsidies (Groff, 2015).

Whether cover crops increase or decrease main crop yield remains under debate (Kaspar and Bakker, 2015). Several studies have demonstrated that cover crop adoption can increase the main crop yield (Chalise et al., 2019; Vendig et al., 2023). Yet, other studies have reported no significant impact or negative effect of cover crops on main crop yield (Sanchez et al., 2019; Deines et al., 2022). For instance, the 6th U.S. cover crop survey reported yield increases of 2% for corn, 2.6% for wheat, and 5% for soybean with cover crop adoption (CTIC, 2022). Conversely, some regional studies have presented contrasting trends. Field experiments using cover crops have reported a corn yield reduction of 3.5% in the United States Midwest (Qin et al., 2021), and a wheat yield decrease of 10% in Colorado (Nielsen et al., 2016). Similarly, findings from the Pampas region in Argentina and Iowa in the United States have indicated a modest adverse impact of cover crops on soybean or corn yield (Alvarez et al., 2017; Acharya et al., 2022). Additionally, a large-scale satellite-based estimation highlighted minor maize and soybean yield reductions associated with cover cropping in the United States Midwest (Deines et al., 2022). These conflicting results can be attributed to different factors, including cover crop species (i.e., leguminous vs. non-leguminous), main grain crop types (i.e., soybean, corn, wheat) (Singh et al., 2020), main grain crop management (i.e., fertilization, tillage) (Malone et al., 2022), and climatic conditions (Nielsen et al., 2016). In terms of the impact of different cover crop species, a recent systematic review documented a 20% main crop yield enhancement with legume cover crops (Zhao et al., 2022). Another meta-analysis indicated a similar yield increase with mixtures of leguminous and non-leguminous cover crops, but no yield impact was found with non-leguminous cover crops such as cereal rye, wheat, oat, and ryegrass (Miguez and Bollero, 2005). However, the positive yield impact of leguminous cover crops is not always consistent. Extreme droughts or floods generally diminish the N-fixation benefits of leguminous cover crops and thus could offset expected yield gains (Daryanto et al., 2018; Peng et al., 2020). Specifically, a lower corn yield increase with leguminous cover crops was reported when annual precipitation is less than 600 mm or higher than 1000 mm (Rusinamhodzi et al., 2011). The crop yield impacts are further complicated when cover crops are combined with other agricultural management practices. Cover cropping plus tillage was reported to reduce soybean yields by 245 kg/ha compared to cover cropping plus no-till (Dozier et al., 2017). Another study, however, reported cover cropping plus reduced tillage resulted in a 3% reduction in corn yield (Snapp and Surapur, 2018). When integrating with other agricultural practices, assessing the crop yield advantages induced by cover cropping becomes challenging due to their susceptibility to various influencing factors such as soil N concentrations (Mazzoncini et al., 2011), moisture conditions (Bayala et al., 2012), and soil texture (Blanco-Canqui and Ruis, 2020; Cordeiro et al., 2021).

It is inherently challenging for field-based experiments to incorporate numerous factors and account for various potential cover crop-related scenarios. By now, few meta-analysis have attempted global assessments of cover crops on yield, only several studies conducted regional quantitative syntheses or utilized large-scale satellite estimations. The intricate task of segregating the effects of cover crops from those of tillage, fertilization, irrigation, and various physical soil conditions necessitates a comprehensive and systematic synthesis based on global field-based cover cropping cases. Therefore, the primary objective of this meta-analysis was to rigorously examine, utilizing all available peer-reviewed field data to date, whether and under what circumstances cover crops exhibit the potential to either enhance or diminish crop yield.

2. Materials and methods

2.1. Literature data compilation

The literature survey process comprises the steps of “Identification”, “Screening”, “Eligibility”, and “Inclusion” to extract yield data from both the Web of Science and the Google Scholar databases. Two keywords “yield” and “cover crop” were used to query the databases and identify literatures. To be considered for inclusion, source publications had to be research articles published in English and accessible through peer-reviewed journals. Following screening, the literature was refined for eligibility based on several inclusion criteria including (i) main research objects comprising main grain crops; (ii) raw yield data were collected from field trials; (iii) original grain crop yield was provided, with cover cropping as the sole variable responsible for yield variation; and (iv) experimental design and crop management details were indicated, including sample size, cover crop species, and tillage type. Details for literature filtering including query phrases, filtering process, exact article number, and criteria explanations are provided in Fig. S1.

After screening a total of 2904 articles from the Web of Science and the Google Scholar databases, we identified 104 publications that meet our criteria, resulting in 1027 yield records for meta-analysis. All the raw yield records are accessible through Table S1. The yield dataset consists of 3881 replicated experiments conducted across 20 countries worldwide (Fig. 1). These yield data were either obtained directly from tables or extracted from graphs using WebPlotDigitizer (Rohatgi, 2015). In conjunction with the yield data, additional supplementary details were collected and associated with relevant crop yield records, including experimental site location, cover crop and main crop species, duration of cover cropping, field physical factors (i.e., soil texture, precipitation, temperature), and field management practices (i.e., rotation, N fertilizer inputs, irrigation, and tillage). This comprehensive dataset was built to detect crop yield variation under different cover cropping scenarios such as utilizing cover crops combined with tillage/no-tillage, fertilized/unfertilized, and drylands/non-drylands. Each independent record was regarded as a basic meta-analysis unit.

Within these supplementary details, all the management practices such as tillage, fertilization, and irrigation refer to operations performed on the main crops. To maintain yield data independence in our analyses, we only used one pair of yield data as independent records. During data collection, there were cases in which several yield data points were extracted from the same publication, only when multiple practices such as cover crop types, tillage, fertilization, and irrigation were implemented. All the cover crop species were grouped into three types: leguminous, non-leguminous, and mixture. Corn, soybean, and wheat

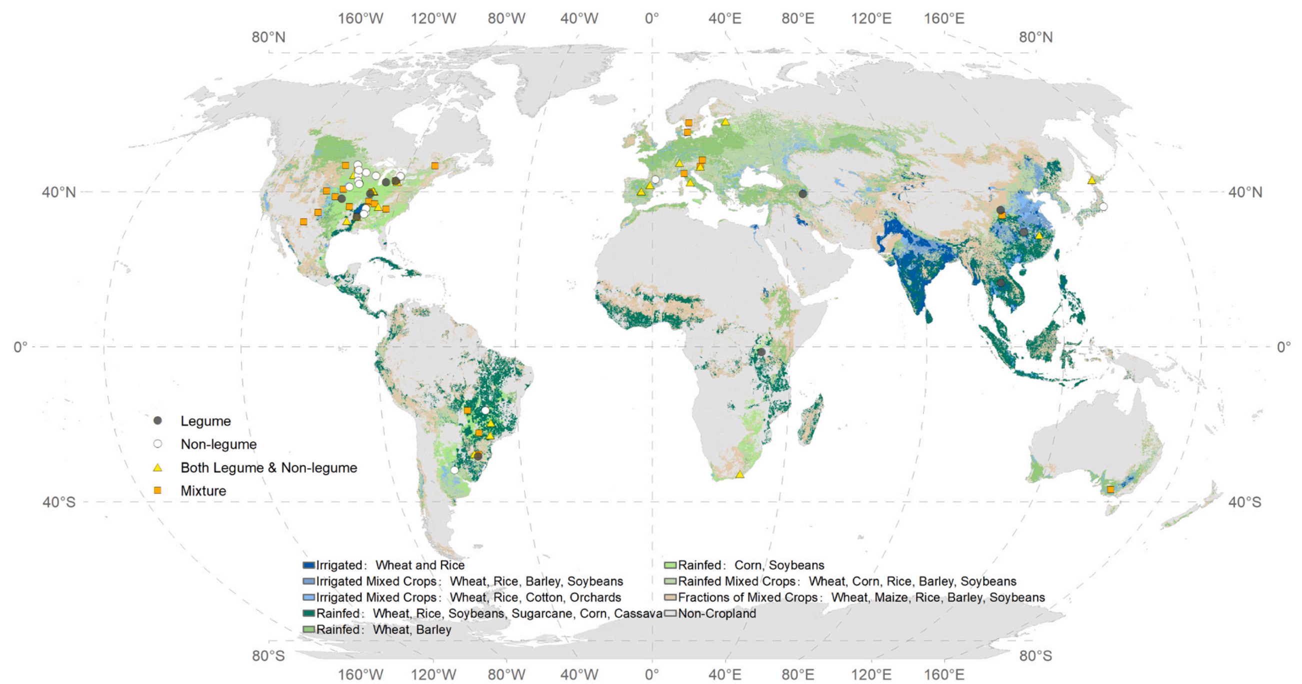

Fig. 1. Global distribution of study sites included in this review. The cropland class map is modified from the Global Food Security Support Analysis Data (GFSAD) Crop Mask Global 1-km dataset (Gumma et al., 2017).

were the major main crop species considered in the database; crops such as sorghum, rice, and barley were categorized as others. As was done in a previous global-scale meta-analysis (Daryanto et al., 2017b), soil texture was grouped into fine texture (clay, clay-loam), medium texture (loam, silt-loam, silty-clay-loam), and coarse texture (loam-sandy, sand, and sandy-loam). Since precipitation information is not reported in some publications, we extracted the aridity index (AI) from the Global Aridity Index and Potential Evapotranspiration Database (Trabucco and Zomer, 2018) using the coordinates of each study site and AI as a reference indicator of moisture condition (Yu et al., 2021; Zomer et al., 2022). Areas with AI > 0.65 were defined as non-drylands (Wang et al., 2012; Wang et al., 2022). For cover cropping duration, if a study reports main crop yield data in a continuous time series, the yield of each year was recorded separately with an indication of cover cropping duration (e.g., 1–4 years) in the dataset.

2.2. Meta-analysis

To quantify the impacts of cover crops on yield in different settings, meta-analysis was used to construct the confidence intervals for each of the aforementioned categorical variables. Here, we used the response ratio as the effect size index in the meta-analysis, which is defined as the ratio of the experimental group (i.e., with cover crop) mean and control group (i.e., without cover crop) mean. In this study, yield varied significantly due to differences in main crop species and growing conditions. Consequently, the collected yield data exhibited a skewed distribution. To achieve a normal distribution of yield response ratio, we denoted the natural logarithm-transformed response ratio (lnR) to represent the metric quantifying the relationship between experimental and control groups (Hedges et al., 1999). lnR was computed as:

$$\mathrm{lnR} = \ln(\overline{\mathrm{X}}_{\mathrm{E}}) - \ln(\overline{\mathrm{X}}_{\mathrm{C}}) \tag{1}$$

where $\overline{\mathrm{X}}_{\mathrm{E}}$ and $\overline{\mathrm{X}}_{\mathrm{C}}$ represent the average yield of experimental group data and control group data, respectively.

For every yield record, both sample size and variance were extracted from the source paper and used as a surrogate for weight in meta-analysis if available. During the extraction, the sample size was always available. For the missing variance, we used the mean-variance of the control group or examined group as a replacement. Since yield magnitude varied significantly between different main crops, the mean-variance was respectively calculated by main crop species such as corn, soybean, wheat, rice, and sorghum. The variance of effect size ($v_{\ln R}$) was calculated by the delta method approximation shown in the equation below (Huang et al., 2018):

$$v_{\ln R} = \frac{(SD_E)^2}{n_E \overline{X}_E^{\,2}} + \frac{(SD_C)^2}{n_C \overline{X}_C^{\,2}} \tag{2}$$

where SD represents the standard deviation, n represents the sample size, and $\overline{X}$ represents the average value of yield. The subscripts E and C represent the values of the experimental group and control group. The weight associated with i^{th} yield record is the reciprocal effect of $v_{\ln R}$ noted as W_i. That is, the smaller the $v_{\ln R}$ of yield record the larger the weight assigned in meta-analysis. The average value of effect size ($\overline{\theta}$) was computed as Eq. (3):

$$\overline{\theta} = \frac{\sum W_i \theta_i}{\sum W_i} \tag{3}$$

where θ_i represents the i^{th} effect size value.

Bootstrapped confidence limits were determined using the statistical software MetaWin 3.0 (Rosenberg et al., 1997). Bootstrapping was iterated 9999 times to calculate a 95% confidence interval (CI) around the cumulative mean effect size for each categorical variable. If the estimated range within 95% CI is larger than zero, it indicates that cover crops positively impacted the main crop yield, and vice versa. The yield impact was considered not significant (no statistical difference between cover cropping and no-cover cropping) when the estimated 95% CI overlaps zero. The forest plot with the error bar was drawn using GraphPad Prism 9.0. To present the magnitude of the effect of cover crops relative to without cover crops, the percentage change of the effect size was calculated using Eq. (4):

$$\text{Change Rate}(\%) = (e^{\ln R} - 1) \times 100\% \tag{4}$$

3. Results

3.1. Overall cover crop impacts

Our results showed that cover cropping has led to an overall moderate increase in main crop yield, amounting to 2.6% (Fig. 2 A). The estimated 95% CI ranged from 1.6% to 3.5%. The yield change was relatively symmetrical, with 43.4% of the records showing a yield reduction and 53.7% showing a yield increase. Concerning different cover crop species, the results showed a 9.8% yield enhancement with leguminous cover crops such as pea, vetch and clover. Non-leguminous cover crops such as rye, oat, and canola, and mixture cover crops, which are often adopted to improve soil biodiversity and physical conditions, showed no statistical improvement in crop yield (95% CI overlapped with 0). Zooming into the frequency distribution, the 25–75% percentile of leguminous cover crops ranged from 0% to 17.1%. For non-legume and mixture cover crops, these percentiles varied from −6.8–7.7% and from −8.7–7.5%, respectively (Fig. 2 A). Besides the difference between legumes and non-legumes, the number of cover crop species also affected main crop yield. Single-species cover cropping resulted in a 3.7% yield increase, and that yield impact reached 9.8% when the single cover crop is a legume. Yet, double-species and multi-species (>3) cover cropping strategies had no significant yield impact (Fig. 2B).

Among the main crops, corn had a 4.7% yield increase in response to cover cropping. Soybean and rice did not show any statistically significant yield change in response to cover cropping (Fig. 2 C). Barley exhibited the highest yield increase (8.3%) but with a wide CI (range: 3.5–13.2%). Wheat experienced a 4.0% yield reduction under cover cropping.

3.2. Impacts of physical conditions and management practices

Soil texture and climate conditions were examined as physical factors affecting yield response. Soil texture is known to affect yield through its impact on soil water and nutrient availability. Cover crops increased yield by 12.9% and 15.2%, respectively in loamy sand and sandy loam soil (coarse-textured). In contrast, in fine-textured soils, the practice induced a main crop yield reduction of 4.8% and 9.6% in clay-loam and clay soils, respectively (Fig. 3 A). For soils with high silt content (silty clay, silty clay loam, loam), no significant impact on main crop yield was found (CI overlapped with zero). We also examined the yield response to cover cropping under different moisture conditions (excluding irrigation) and found a yield increase of 11.4% for cover cropping in drylands under rainfed conditions (Fig. 3B). The effect size bias was low considering heterogeneity being minimal ($I^2 < 10\%$). As for non-drylands under rainfed conditions, the 95% CI overlapped with zero, indicating no significant impact of cover cropping on yield. Moderate heterogeneity was reported with I^2 less than 50% based on the Chi-squared statistic.

The effect of management practices (tillage, fertilizer application, duration of cover cropping) was examined. Results showed that cover cropping plus conventional tillage (CT) resulted in a 6.9% increase (Fig. 4 A), whereas cover cropping plus no-till (NT) had no statistically significant impact on main crop yield (95% CI overlapped with zero). A 10.5% yield increase was observed when cover cropping was implemented without fertilizer, but the yield increase was only 1.8% when cover cropping was combined with fertilizer. These results provided evidence that cover crops are most beneficial under nutrient-limited conditions. Besides, main crop yield increased with a longer duration of cover cropping. The amount of main crops yield increased by 1.8% to 1.9% in the first two years of using cover crops. After three and four years, the increase became bigger, reaching 6.7% and 11.6%, respectively.(Fig. 4B). Interestingly, no yield increase was observed with longer duration. A yield reduction of 7.2% was recorded with duration > 4 years.

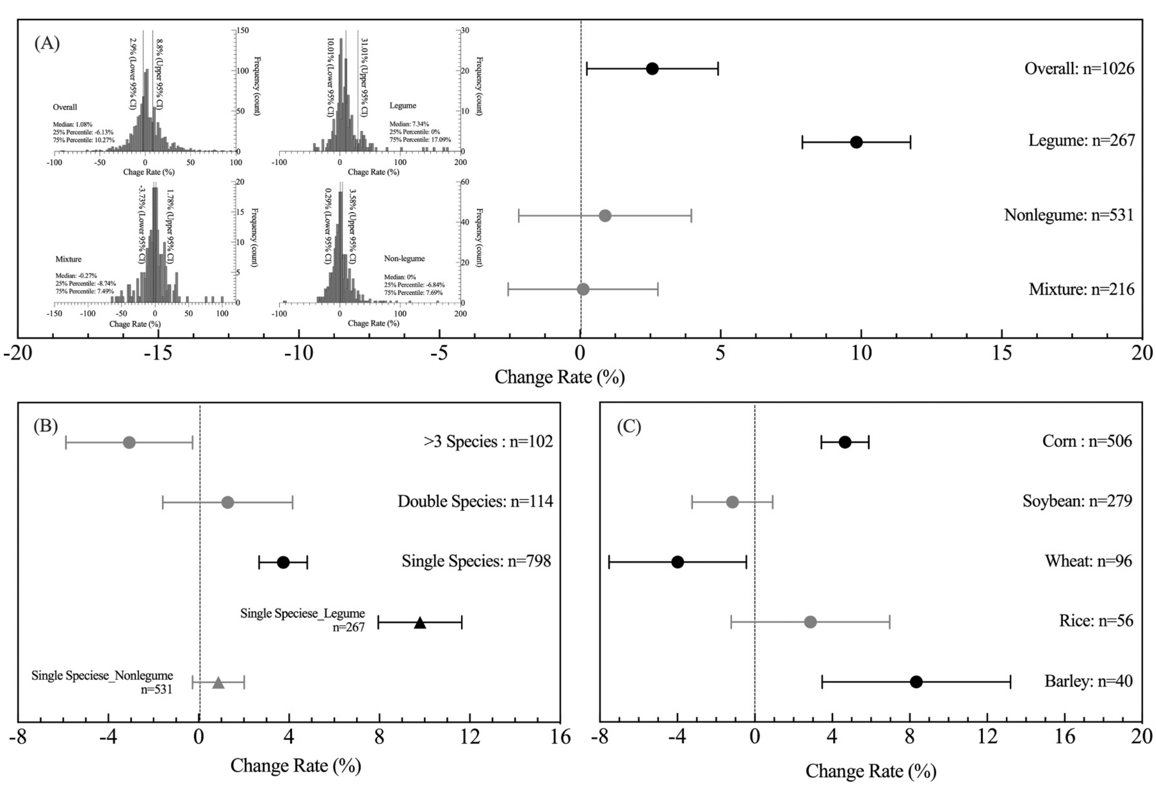

Fig. 2. Yield variation and frequency distribution under different types of cover crops (A), yield variation under different numbers of cover crop species (B), and yield variation under different types of main crops (C). Black dots represent the mean ln$R$ with the error bar indicating the 95% CI. The letter "n" indicates the number of records involved in the calculation. P-values are less than 0.05 in all the above figures. The gray bars indicate the estimated 95% CIs overlap with zero.

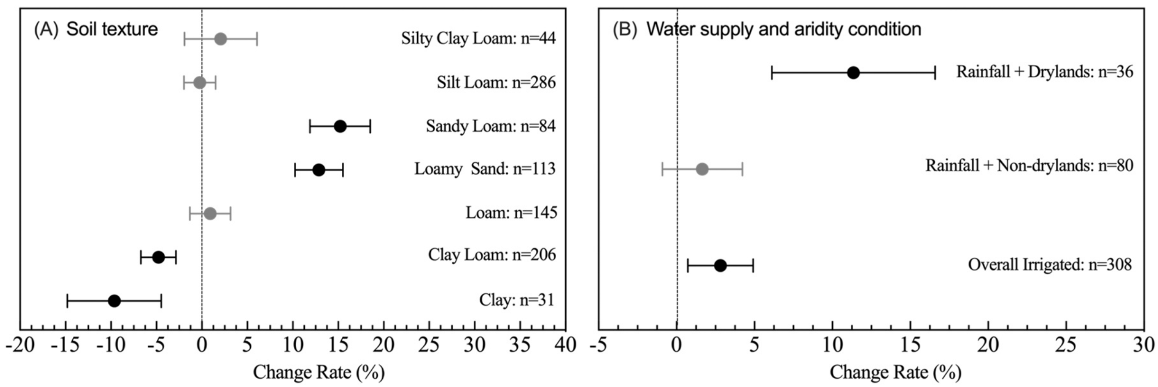

Fig. 3. Main crop yield responses to soil texture (A) and water supply and aridity condition (B). Black dots represent the mean lnR with the error bar indicating the 95% CI. The letter "n" indicates the records number of records involved in the calculation. P-values are less than 0.05 in all the above figures. The gray bars indicate the estimated 95% CIs overlap with zero.

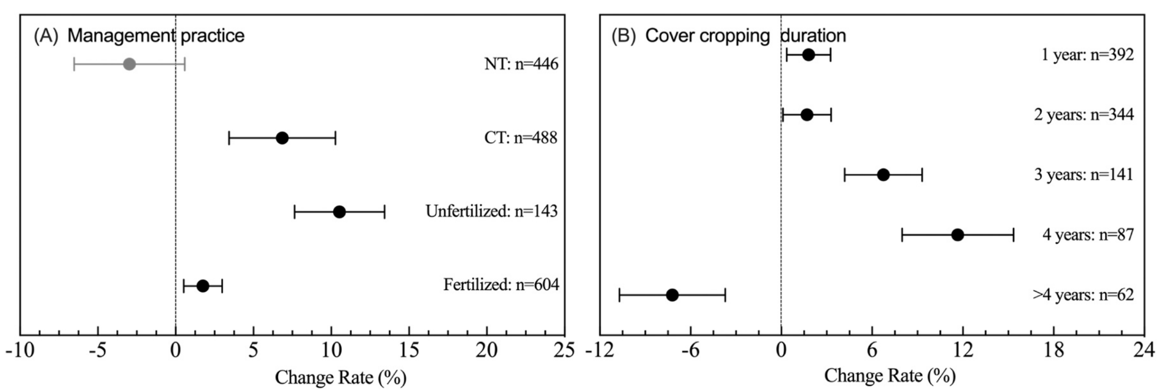

Fig. 4. Main crop yield responses to different management practices (A), and cover cropping duration (B). Black dots represent the mean lnR with the error bar indicating the 95% CI. The letter "n" indicates the number of records involved in the calculation. P-values are less than 0.05 in all the above figures. The gray bars indicate the estimated 95% CIs overlap with zero.

4. Discussion

Cover crops provide an opportunity to benefit both food security and climate. The primary obstacle to the widespread adoption of cover crops is the concern of a decreasing yield of main crops. To alliviate the obstacle, this study determined the extent to which cover crops impact the yield of main crops,and identified conditions under which yield penalties can be minimized and yield benefits can be maximized. The results indicated a modest yield increase after the adoption of cover crops across global cases. Specifically, the overall main crop yield increase of 2.6%. Such results are consistent with prior research. A newly published meta-analysis reported cover cropping simultaneously increased yields and SOC in 59.7% of 434 paired observations globally (Vendig et al., 2023). Given that cover crops are often utilized in conjunction with other management practices and occur across various meteorological and soil conditions, we further identified the specific conditions that promote or reduce yield, as well as the underlying mechanisms.

4.1. Yield enhancement scenarios

Yield variability by cover cropping is a trade-off between providing soil ecological services and depleting N and soil moisture for the main crop. Our results showed the utilization of leguminous cover crops, cultivation in coarse soil texture and dryland areas, and the implementation of longer cover cropping durations are scenarios conducive to enhanced crop yields. Considering the interaction of mineral fertilizer with the N-fixing ability of cover crops, tillage practice with soil texture, and irrigation with aridity conditions, we discussed the optimal scenarios that can maximize the yield-promoting effect.

Leguminous cover crops such as vetch and clover are commonly recognized as beneficial to subsequent crop yield with N-fixing ability, which can enhance N inputs derived from atmospheric N via biological N fixation (Kakraliya et al., 2018). Given the fact that the use of winter leguminous cover crops for erosion control and to provide additional N to the soil is well-established (Torbert et al., 1996), it is not surprising to observe better yield performance by leguminous cover crops compared to non-leguminous cover crops (Fig. 2 A). However, fertilization tends to negate the positive yield effects of leguminous cover crops. We noticed that leguminous cover crop yield increase is 13.4% lower with fertilization than without fertilizer use (Fig. 5 A). That is not to say that fertilizing main crops will result in lower yields. The use of leguminous cover crops can fix N and further lead to yield-increasing benefits compared with no-cover cropping when the main crops are not fertilized. This finding corroborates with previous quantitative synthesis and meta-analysis (Miguez and Bollero, 2005; Daryanto et al., 2018). Liebig's law explains this, that is, the yield of plants is limited by the element in the least available quantity (Chapin et al., 2002). Specifically here, in actual field practice, excessive N is usually added through fertilization (thus removing the limitation), other resources such as water and temperature may become limiting factors for the main crop yield as suggested by Qin et al. (2021). Referring to cover cropping without fertilization, leguminous cover crops (21.8%) resulted in a higher yield increase than non-legumes (4.9%). Evidence from Montana also supported these results. Miller et al. (2023) found that fertilized wheat under cover cropping is often susceptible to "haying off" and

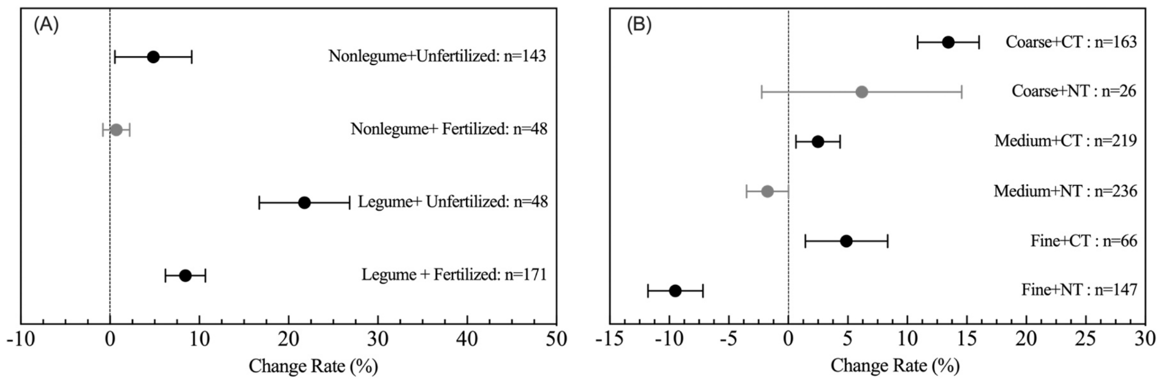

Fig. 5. Main crop yield response to combined effects of cover crops with fertilization (A), different soil texture and tillage combination (B). Black dots represent the meanlnR with the error bar representing the 95% CI. Letter n indicates the number of records. The p-values indicate the statistical differences between various groups, and in both figures, these values are less than 0.05. The gray bars indicate the estimated range within 95% CIs overlap zero.

leads to lower yield than cover cropping-only practice. The interpretation is that during the grain fill period, fertilization maintaining vigorous early wheat biomass production consumes too much water, resulting in reduced harvest index and grain mass (Herwaarden et al., 1998). Slightly different from our expectation is that leguminous cover crops induced a greater yield increase (8.4%) compared to non-legume under fertilizer treatment (Fig. 5 A). One possible explanation is that improper fertilization strategies (e.g., timing of N application) lead to N loss through leaching and runoff before N uptake by the main crops. Legume cover crops can slowly release nutrients (including fixed N) from decomposing biomass and remain effective in boosting yield compared to non-legumes.

Other modulating factors of crop yield enhancement include soil texture and tillage practice. It appeared main crop yield enhancement is greater in coarse-textured (e.g., loam-sandy and sandy-loam) than in fine-textured soils. A prior study reported a similar finding using a soil water retention model that medium or coarse-textured soils respond quicker to cover cropping than fine soils (Rawls et al., 2004a). Cordeiro et al. (2021) explained that sandy soils benefit more than fine-textured soils from cover crops by reducing N leaching and soil carbon losses as well as improving soil microbe activities. Considering tillage causes the breakdown of soil aggregates, NT or CT may alter the existing soil texture effects on yield under field conditions. We further detected the combined effect of cover cropping and tillage under different soil textures. The results showed that cover cropping plus NT has no yield benefit in coarse-textured soils. Needelman et al. (1999) indicated that NT practices did not affect the vertical distribution of SOC, total N in soil with high sand content, which partly explained why NT made no difference in coarse-textured soils. Besides, cover cropping plus CT led to a 2.5% yield increase in medium-textured soils, and a 4.8% yield increase in fine-textured soils compared to cover cropping with NT practice (Fig. 5B). These results seem to be different from the common expectation that NT practices can improve soil conditions. Kalaiselvi et al. (2023) suggested that soil physical parameters were responsive to NT implementation in the long-term (30 years). However, in the short term (5 years), they observed improvement varied depending on soil depth and soil texture. Considering long-term cover cropping experiments are not common and thus less well represented in this analysis, these results mainly reflect short-term yield feedback by cover cropping plus CT. The interpretation for the observed short-term yield advantage by CT plus cover crops lies in the fact that, before the long-term benefits (such as increasing water infiltration and reducing soil bulk density) of cover crops and NT becomes noticeable, CT may aid in alleviating soil compaction in medium or fine-textured soils (Williams and Weil, 2004).

Introducing cover crops in dryland regions is another yield enhancement scenario if precipitation or irrigation can replenish soil water consumption by cover crops. After cover crop termination, the biomass remaining on the soil surface acts as a protective cover to conserve soil moisture (Hoyt and Hargrove, 1986). Besides, cover cropping also benefits from improving soil aggregation, aeration, water infiltration, and nutrient uptake by the live roots in wetter years (Blanco-Canqui, 2018; Rosa et al., 2019). A two-year experiment in New Mexico suggests cover crops can be successfully grown under limited water availability in irrigated arid systems of New Mexico while still improving soil quality (Agarwal et al., 2022). Our results corroborate this. Adopting cover crops in drylands under rainfed conditions led to an 11.4% yield increase, while no statistically significant yield impact under cover cropping in non-drylands (Fig. 3B). For this instance, cover cropping can be regarded as a low-cost alternative to irrigation (Delgado et al., 2007). Bayala et al. (2012) proposed a precipitation threshold for these different impacts. When annual precipitation is below 600 mm, cover crops are generally more beneficial to main crop yield than other conservation agriculture practices in drylands. Garba et al. (2022) indicated that 700 mm represents a switch point to achieve significant main crop yield benefits of cover cropping in drylands. However, cover cropping plus non-irrigation should be adopted with caution especially when moisture conditions are low and approach the main crop water stress point.

4.2. *Yield impairing scenarios*

Cover crops are yield-effective in some cropping systems and environments, but not under all conditions. Each cover crop has limitations that may impair yields. Some of these limitations directly cause a decrease in yield, while others reduce the effect of yield enhancement. The use of non-legume cover crops, introducing them to fields no-till with a short term, especially in fine-textured soils are more likely to impair crop yield than to induce yield benefits.

We examined several variables controlling crop yield across different continents and observed that the general response was positive, noting a median yield increase of 6.1%. In North America, the median yield increase of cover crops was 1.2%, which was relatively modest compared with Europe, Asia and the Pacific, and South America (Fig. 6 A). These results are somewhat different from those of some prior studies. For example, Deines et al. (2022) reported that cover cropping had led to a 5.5% yield loss on corn using validated satellite data products across the U.S. Midwest region. Yet, when zooming into the Midwest using our dataset, we found that the effect of cover crops on crop yields is neutral in this region, which is lower than the average effect in North America. The median yield values for legume and non-legume cover crops in the Midwest were 2.9% and −0.5%, respectively (Fig. 6B). The meta-analysis results indicated that legume cover crops had a positive yield increase (4.9%) while non-legume had no impact on yield in the Midwest. The non-favorable yield impact of non-legumes was also

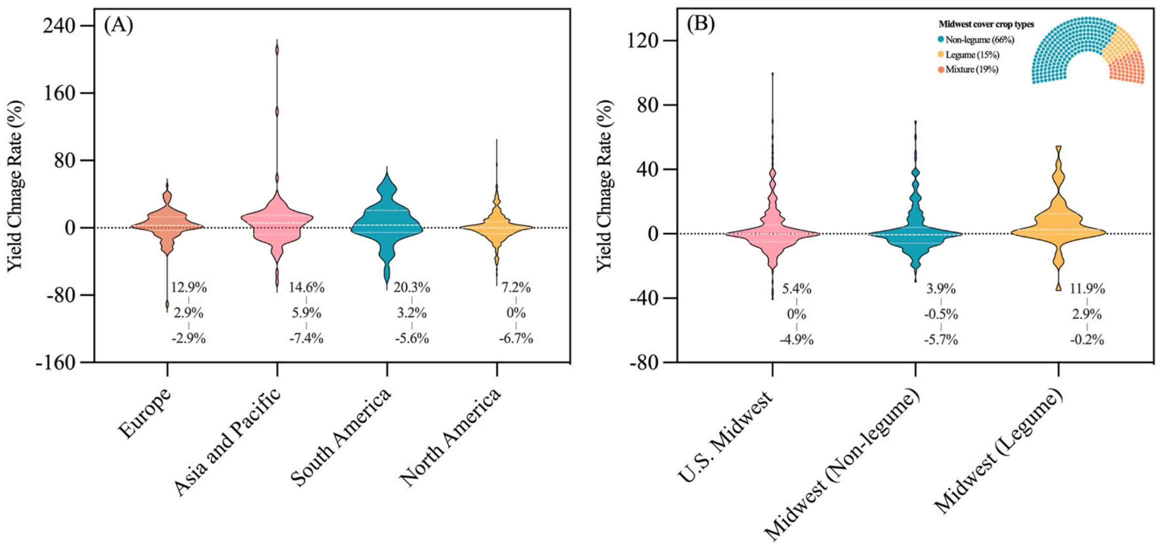

Fig. 6. Overview of yield change rate (%) from different continents (A), different regions and cover crop types (B). The numbers on each violin plot indicate the first quartile, median, and third quartile values, respectively. The parliament chart notes the percentage of legume/non-legume records contained in this analysis from the Midwest U.S.

observed in other crops. For example, Abdalla et al. (2019) conducted a meta-analysis and found that non-leguminous cover crops resulted in a greater reduction of cereal yield compared to legumes, with an average loss of 4.0%. About 66% of the cover crops in our analysis are non-leguminous and only 15% are leguminous. The dominant non-legume cover crops in corn-soybean rotations in the Midwest region likely resulted in the yield loss observed in Deines et al. (2022).

Previous work has pointed out the risk of yield loss in main crops due to cover crop plus NT for a short duration (Pittelkow et al., 2015). Brouder and Gomez-Macpherson (2014) pointed out that increased soil compaction under NT may have a direct effect on the risk. Besides, conservation practices such as cover cropping and NT, when combined, may increase the weed and pest pressure in the short term (Mashingaidze et al., 2012; Su et al., 2021). Moreover, the beneficial soil properties from cover crops and NT (increases in soil C, aggregate stability, and available water capacity) take time to develop (Kumar et al., 2012; Pittelkow et al., 2015). As such, it is not surprising to observe that cover crops plus NT show non-significant effect on crop yield compared with cover crops plus CT, especially considering that 68% of the data included in this analysis were from short-term experiments of 1–4 years of duration (Fig. 4 A). We suggest that NT duration should be identified as an influential variable controlling cover cropping benefits. Adopting other management practices such as weed control and soil compaction alleviation could be considered to shorten the period of yield penalty when cover cropping and NT are implemented in tandem. Further, the duration of NT implementation before introduction of cover cropping also appears to have an effect. Blanco-Canqui and Jasa (2019) conducted a 15-year-long field experiment and suggested that introducing cover crops to long-term continuous NT fields may have smaller or slower benefits compared to short-term NT or intensive tillage before cover cropping. We need to point out that, when considering the combined effect of NT and cover crops, soil texture should be considered in the discussion. Upon our closer inspection, cover crop plus NT resulted in a 9.5% yield reduction in fine-textured soils compared with positive yield returns under cover cropping plus CT (Fig. 5B). Regarding the lag period of cover cropping and NT, fine-textured soils are more susceptible to compaction (Hatten and Liles, 2019). Besides, fine-textured soil with high water-holding capacity may offset the benefit of improved water infiltration and greater soil moisture by cover cropping and NT (Serraj and Siddique, 2012), which leads to slower development of other additional benefits such as increasing SOC than medium- or coarse-textured soils (Rawls et al., 2004b). We suggest extra attention should be paid and additional management should be adopted when implementing NT plus cover crops in fine-textured soils to avoid yield penalties, especially in the early years of cover cropping implementation.

As for cover cropping duration, prior studies reported improvements in major crop yields and soil properties over time (Blanco-Canqui and Jasa, 2019; CTIC, 2022). Our findings on short-term durations (shorter than 4 years) suggest that cover cropping leads to year-to-year yield increases (Fig. 3B). Yet, the yield reduction observed with long-term cover cropping (longer than 4 years) was contrary to our expectations. However, given the relatively small sample size and high heterogeneity of this data subset, these results should be interpreted with caution. Nonetheless, such a reduction calls attention to the potential risk of yield penalty from decades of cover cropping. Although decades-long cover cropping research is not common, available information seems to indicate a weakening effect of long-term cover cropping on soil properties and crop yield improvement. A long-term field experiment in Nebraska indicated that, while the positive effects of leguminous cover crops on soil properties disappeared, grass cover crops continue to have a stronger impact on soil properties after twelve years of cover cropping (Blanco-Canqui and Jasa, 2019). A ten-year study across 39 sites in Iowa suggested no significant improvement in main crop yield attributable to the use of cover crops, although cover crops reduced soil erosion and nutrient loss in runoff (Comito et al., 2020). One possible explanation is the requirement for additional machinery to sow cover crops led to increased soil compaction. Planters and spreaders usually require at least two additional trips into the cover-cropped fields in the Midwest, thereby increasing the risk of compaction. Additionally, in long cover cropping duration, grazing on cover crops by livestock may also result in surface soil compaction due to excessive trampling, potentially suppressing subsequent crop growth (Obour et al., 2021), although this is not commonly highlighted as a major concern.

4.3. *Yield variability synthesis*

As a management practice within the framework of climate-smart agriculture (CSA), cover cropping is anticipated to enhance crop yield in general (Daryanto et al., 2018; Fan et al., 2021; Van Eerd et al., 2023). However, the impact of cover cropping on yield is still debatable. The influence of cover cropping is a consequence of various combined effects, including cover crop species, duration of cover cropping, rainfall, irrigation, fertilization, tillage, and soil texture. It is challenging to draw definitive and general conclusions as to whether cover cropping is beneficial to main crop yield for all cases. Here, we summarized the available data from cover cropping studies conducted across the globe and aimed to synthesize the conditions that are suitable or not suitable for cover cropping.

The main variability of cover cropping impacts on yield is related to the water and N supply. One typical example related to N supply is rye. Although legume cover crops are N-fixing and yield-boosted types, rye is often preferred due to its ability to withstand harsh winter conditions and sandy soil in the Midwest region of the U.S., as documented by Martinez-Feria et al. (2016). That is why yield increase was low in the Midwest as reported in prior research (Deines et al., 2022). N supply also varied when cover cropping was applied with different fertilizer management practices. In light of our analysis, slow-release N by leguminous cover crops facilitated better main crop yield under unfertilized field conditions (Fig. 7). The optimal integration of cover crops alongside specific N application types, quantities, and timing is crucial to main crop yield and thus further impacting the net economic return of adopting cover crops (Wang et al., 2023).

Water availability is another vital factor affecting yield variability. Nielsen et al. (2015) suggested cover cropping is a problem rather than a solution to yield in drylands due to the extra water consumption. Adil et al. (2022) supported this, indicating that cover crops deplete water before main crops. However, the actual yield variation caused by water availability variation is multifaceted. Under the wet season in drylands or when there is sufficient precipitation, cover crops allow for greater infiltration rates, in return saving enough water from running off to make up for the water used to grow the cover crops (Rosa et al., 2021a; Rosa et al., 2021b). The evidence of successful wheat yield after a wet winter in California drylands system (McGuire et al., 1998) is consistent with this line of perspective. Our result of a higher yield return in rainfed drylands also supports this (Fig. 7). However, we need to note that cover crops can adversely affect the yield of the main crop yield under aggravating a wet soil condition. The primary risk associated with this scenario is oxygen depletion induced by improper irrigation or flood, particularly in low topography or clay-rich soil regions (Philippot et al., 2013; Qin et al., 2021). Introducing cover crops under specific aridity and precipitation conditions may positively impact yields. As previously mentioned, 500–700 mm annual precipitation is suggested as the switch point. Besides, choosing an appropriate termination timing is another potential way to offset adverse effects on soil water (DeVincentis et al., 2022). Unfortunately, there is not a sufficient amount of data on cover crop termination timing in this analysis for us to examine the termination timing impact. The description of termination timing in different publications is not quantitative, it was a main barrier for us to include that variable in our analysis. In future work, establishing a uniform metric (e.g., the number of days after or before the main crop) is recommended when examining the effects of termination timing on water consumption and yield.

From the view of local producers, cover cropping is not a zero-sum game. There is a basket of choices that could be chosen to achieve optimal scenarios. For example, adopting CT in fine-textured soils with cover cropping can convert yield reduction to yield increase (Fig. 7). Besides, using leguminous cover crops directly adding soil N input or non-legume cover crops scavenging nutrients for the next subsequent crops can obtain better yield return than relying on mineral fertilizer addition (Fig. 5 A). In addition, even when cover cropping is neutral or slightly impairing yields, farmers may still achieve overall positive returns by reducing fertilizer or irrigation expenses and receiving government subsidies. At the current rate in the U.S., a $5 per hectare subsidy is available for eligible farmers to cover the cover cropping practice (Zhou et al., 2022). Although the amount is small compared with the $25 cost of seeds and $12 expense of seeding per acre, it helps farmers get through the beginning years of cover cropping before the practice starts to pay off. Our results suggested that more than two years of cover cropping is needed to make it a profitable investment (Fig. 7). Although our findings indicated the general profitability of cover crops, we still advise their targeted application for specific purposes rather than attempting to address all field issues. In fields where no-till practices are already established, the primary focus when using cover crops should be on enhancing infiltration and maximizing N input or N-fixing abilities, rather than solely targeting soil moisture improvement. This is because both no-till and cover crops have similar effects, increasing residue coverage and subsequently reducing soil water evaporation. Additionally, suppose cover crops are aimed to decrease evaporation in dryland areas, the termination time is crucial to avoid soil moisture depletion during the main crop growth period.

Given the fact that cover crops affect the subsequent main crop yield is an integrated process influenced by multiple factors, therefore, the variability in the observed impact of cover crops on yield is predictable.

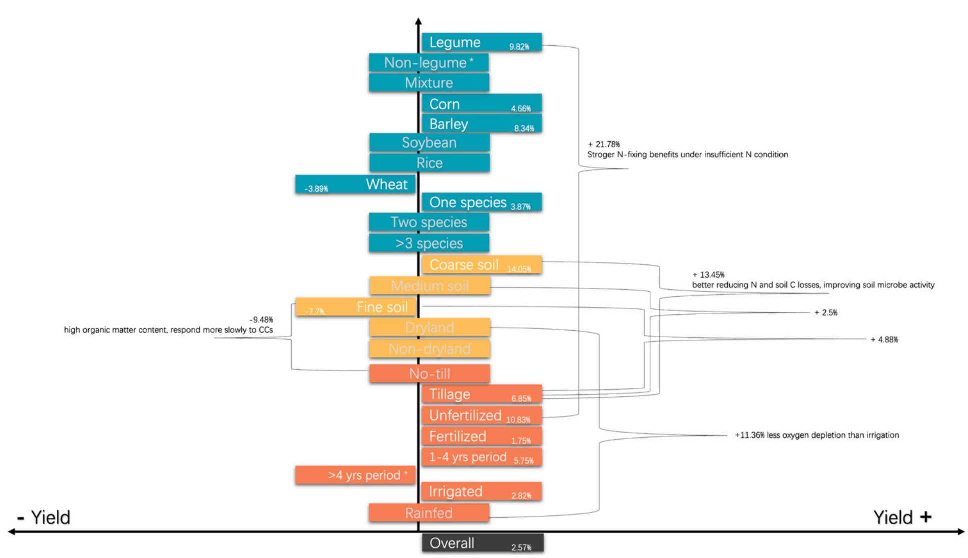

Fig. 7. Yield response tree containing different factors of cover crops (green bars), field physical condition (yellow bars), and management practice (orange bars). Bars overlap with y axis representing no statistical difference. Black brackets note combinations that may change the yield response. The underlying interpretation of yield change is labeled aside. * indicated high heterogeneity of results.

A quantitative synthesis of the positive or negative impact of cover crops on crop yield is particularly useful. Clarifying the scenarios that lead to positive yield benefits and helping minimize yield-reducing effects could be highly informative to farmers, farm advisors, and extension services.

5. Conclusions

This study provides a comprehensive assessment of the impact of cover crops on subsequent main crop yield through the synthesis of field experimental data at a global scale. The results of the synthesis showed that cover crops led to an overall moderate increase in main crop yield, amounting to 2.6%, but the variability of main crop yield response was substantial. The utilization of leguminous cover crops, cultivation in coarse soil texture and dryland areas, and the implementation of longer cover cropping durations are scenarios conducive to enhanced crop yields. The highest yield increase potential was found when pairing legume cover crops with corn. The use of non-legume cover crops, introducing them to fields under a short-term no-till, especially in fine-textured soils, can impair yields. Utilizing cover crops in coarse-textured soils and under rainfed conditions in drylands tends to improve soil moisture retention and limit nutrient loss, attributes that can translate into crop yield benefits in these water-limited regions. Although our findings suggested the general yield profitability of cover crops, we still advise their targeted application for specific purposes. When implementing cover cropping under no-till cultivation in fine-texture soils, additional management practices should be adopted to control noxious weeds, alleviate soil compaction, and ultimately avoid yield penalties. These supportive measures could also help shorten the lag period (1–3 years) before the increase in main crop yield can be observed following the initiation of cover cropping. The use of cover crops is not a zero-sum game, a basket of strategies are available for selection to attain optimal yield profitability.

CRediT authorship contribution statement

Lixin Wang: Conceptualization, Funding acquisition, Project administration, Supervision, Writing – original draft. **Pierre-Andre Jacinthe:** Funding acquisition, Supervision, Writing – review & editing. **Yu Peng:** Data curation, Formal analysis, Methodology, Writing – original draft. **Wei Ren:** Funding acquisition, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fcr.2024.109343.

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