

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, including soil erosion control, weed suppression, and increased water availability. However, how cover crops impact the succeeding crop yield remains a matter of debate, which is not surprising considering the diverse management practices, soil types, and physical conditions associated with cover crop use. Therefore, the main aim of this study is 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 (1,027 records) and used meta-analysis to quantitatively examine whether cover crops improve or impair yield return, and further identify the conditions under which the yield penalties could be minimized, or the yield benefits could be maximized. Overall we observed that main crop yield increased by 2.6% under cover cropping, with yield increase and yield reduction observed in 43.3% and 53.7% of the cases, respectively. Legume was the cover crop type with the highest yield increase potential with corn as the grain crop type showing the best yield improvement. Leguminous cover crops resulted in a 9.8% yield increase compared to no statistically significant impact by non-leguminous cover crops. Adopting leguminous cover crops without fertilizing main crops resulted in a 21.8% yield increase. We also found that utilizing cover crops did not affect yield if the field had already been introduced to the no-till practice. Introducing cover crops on coarser soils and in rainfed drylands can increase yield by 14.1% and 11.4%, respectively. Cover crop plus tillage converted the 9.5% yield decrease of cover crops plus no-till to the 4.8% yield increase in fine-textured soils. Informed by the results, yield variation of cover crops is mainly affected by nitrogen and soil moisture availability. The nitrogen-

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23 fixing function of leguminous cover crops should be fully utilized, especially when they are used to replace fertilizer application
24 as nitrogen input to main crops, which can bring positive yield and environmental benefits. Introducing cover crops on coarser
25 soil fields and drylands under rainfed conditions is advisable, as cover crops tend to function better in improving soil moisture
26 retention and reducing nutrient loss, attributes that are more likely to lead to crop yield benefits. Particular attention should be
27 paid, and additional management should be adopted such as weed control, fracturing a soil compaction layer, and eliminating
28 ruts, when implementing no-till plus cover crops in fine-textured soils to avoid yield penalties. These supportive measures are
29 also advisable to shorten the lag period of yield increase, especially within the initial 1-3 years of cover cropping
30 implementation. Our analysis addressed the quantitative cover crop impacts on yield and demonstrated the variable cover crop
31 yield impacts under different conditions, which can encourage greater cover crop adoption and help avoid substantial yield
32 penalties. This valuable information could be useful to policymakers and extension services and would facilitate greater and
33 appropriate adoption of cover crops for farmers.

34 *Keywords:* Cover Crops, Cash Crop Yield, Meta-analysis, Conservation Agriculture

35

36 **1. Introduction**

37 High-yield aimed agriculture practices have caused and will continue to cause nitrogen (N) pollution
38 (Daryanto *et al.*, 2017; Abdalla *et al.*, 2019), agroecosystem biodiversity loss (Guerrero-Pineda *et al.*,
39 2022), soil degradation (Muhammad *et al.*, 2021), and other environmental issues (West *et al.*, 2014;
40 Balmford *et al.*, 2018). They have also been reported as the primary cause of pesticide pollution (Elias *et al.*,
41 2018; Larsen *et al.*, 2021), and greenhouse gas emissions (Crippa *et al.*, 2021; Laborde *et al.*, 2021).
42 With the substantial environmental costs of modern agriculture practices, a more climate-resilient and
43 sustainable food production system is called for to meet increasing food demand and cope with
44 environmental sustainability (Hunter *et al.*, 2017; Poore and Nemecek, 2018; Pretty *et al.*, 2018;
45 Jastrzębska *et al.*, 2022).

46 Planting cover crops is a potential choice to reduce the environmental burden (Blanco-Canqui *et al.*,

47 2015; Afshar et al., 2018; Daryanto et al., 2018) while maintaining crop productivity (Tonitto *et al.*, 2006).
48 Cover crops are plants typically cultivated between income-producing crops to cover the soil surface after
49 harvesting main crops. It has been recognized as an effective practice that offers numerous benefits,
50 including improving soil physical and microbial properties (Blanco-Canqui and Ruis, 2020), soil erosion
51 control (Liu et al., 2021; Saba and Christy, 2021), N leaching (Gabriel et al., 2013; Thapa et al., 2018),
52 soil organic carbon sequestration (Jian et al., 2020), greenhouse gas fluxes (Quemada *et al.*, 2020;
53 McClelland *et al.*, 2021; Li *et al.*, 2023), and weeds suppression (Koehler-Cole et al., 2017; Monteiro et
54 al., 2021) among other benefits. Despite having several agro-environmental advantages, cover crops are
55 perceived by farmers as a long-term investment that can hardly pay for themselves quickly (DeVincentis
56 et al., 2020), especially considering cover crops may even impair the yield of main crops (Bergtold et al.,
57 2019). Therefore, at the farm operation level, planting cover crops remains an underutilized strategy.
58 USDA Census Data has shown that cover cropping accounted for less than 5% of all U.S. agriculture in
59 2017 (USDA, 2017; Zulauf and Brown, 2019). In the European Union, more than 23 % of arable land was
60 still left without cover crops during the winter of 2016 (Bellassen et al., 2022), despite the mandatory
61 arable land maintenance Common Agricultural Policy.

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

70 Whether cover crops increase or decrease main crop yield remains under debate (Kaspar and Bakker,
71 2015). Several studies have demonstrated that cover crop adoption can increase the main crop yield
72 (Chalise *et al.*, 2019; Vendig *et al.*, 2023). Yet, other studies have reported no significant impact or negative

73 effect of cover crops on main crop yield (Sanchez *et al.*, 2019; Deines *et al.*, 2022). For instance, the 6th
74 U.S. cover crop survey reported yield increases of 2% for corn, 2.6% for wheat, and 5% for soybean with
75 cover crop adoption (CTIC, 2022). Conversely, some regional studies have presented contrasting trends.
76 Field experiments using cover crops have reported a corn yield reduction of 3.5% in the United States
77 Midwest (Qin *et al.*, 2021), and a wheat yield decrease of 10% in Colorado (Nielsen *et al.*, 2016). Similarly,
78 findings from the Pampas region in Argentina and Iowa in the United States have indicated a modest
79 adverse impact of cover crops on soybean or corn yield (Alvarez *et al.*, 2017; Acharya *et al.*, 2022).
80 Additionally, a large-scale satellite-based estimation highlighted minor maize and soybean yield
81 reductions associated with cover cropping in the United States Midwest (Deines *et al.*, 2022). These
82 conflicting results can be attributed to different factors, including cover crop species (i.e., leguminous vs.
83 non-leguminous), main grain crop types (i.e., soybean, corn, wheat) (Singh *et al.*, 2020), main grain crop
84 management (i.e., fertilization, tillage) (Malone *et al.*, 2022), and climatic conditions (Nielsen *et al.*, 2016).
85 In terms of the impact of different cover crop species, a recent systematic review documented a 20% main
86 crop yield enhancement with legume cover crops (Zhao *et al.*, 2022). Another meta-analysis indicated a
87 similar yield increase with mixtures of leguminous and non-leguminous cover crops, but no yield impact
88 was found with non-leguminous cover crops such as cereal rye, wheat, oat, and ryegrass (Miguez and
89 Bollero, 2005). However, the positive yield impact of leguminous cover crops is not always consistent.
90 Extreme droughts or floods generally diminish the N-fixation benefits of leguminous cover crops and thus
91 could offset expected yield gains (Daryanto *et al.*, 2018; Peng *et al.*, 2020). Specifically, a lower corn yield
92 increase with leguminous cover crops was reported when annual precipitation is less than 600 mm or
93 higher than 1,000 mm (Rusinamhodzi *et al.*, 2011). The crop yield impacts are further complicated when
94 cover crops are combined with other agricultural management practices. Cover cropping plus tillage was
95 reported to reduce soybean yields by 245 kg/ha compared to cover cropping plus no-till (Dozier *et al.*,
96 2017). Another study, however, reported cover cropping plus reduced tillage resulted in a 3% reduction in
97 corn yield (Snapp and Surapur, 2018). When integrating with other agricultural practices, assessing the
98 crop yield advantages induced by cover cropping becomes challenging due to their susceptibility to

99 various influencing factors such as soil N concentrations (Mazzoncini et al., 2011), moisture conditions
100 (Bayala et al., 2012), and soil texture (Blanco-Canqui and Ruis, 2020; Cordeiro et al., 2021).

101 It is inherently challenging for field-based experiments to include all these factors and consider all
102 possible cover crop-related scenarios. Few meta-analyses have attempted a global assessment of cover
103 crops on yield, prior studies have presented quantitative syntheses or utilized large-scale satellite
104 estimations. However, the intricate task of segregating the effects of cover crops from those of tillage,
105 fertilization, irrigation, and various physical soil conditions necessitates a comprehensive and systematic
106 synthesis based on global field-based cover cropping cases. Therefore, the primary objective of this meta-
107 analysis was to rigorously examine, utilizing all available peer-reviewed field data to date, whether and
108 under what circumstances cover crops exhibit the potential to either enhance or diminish crop yield.

109 **2. Materials and methods**

110 *2.1 Literature data compilation*

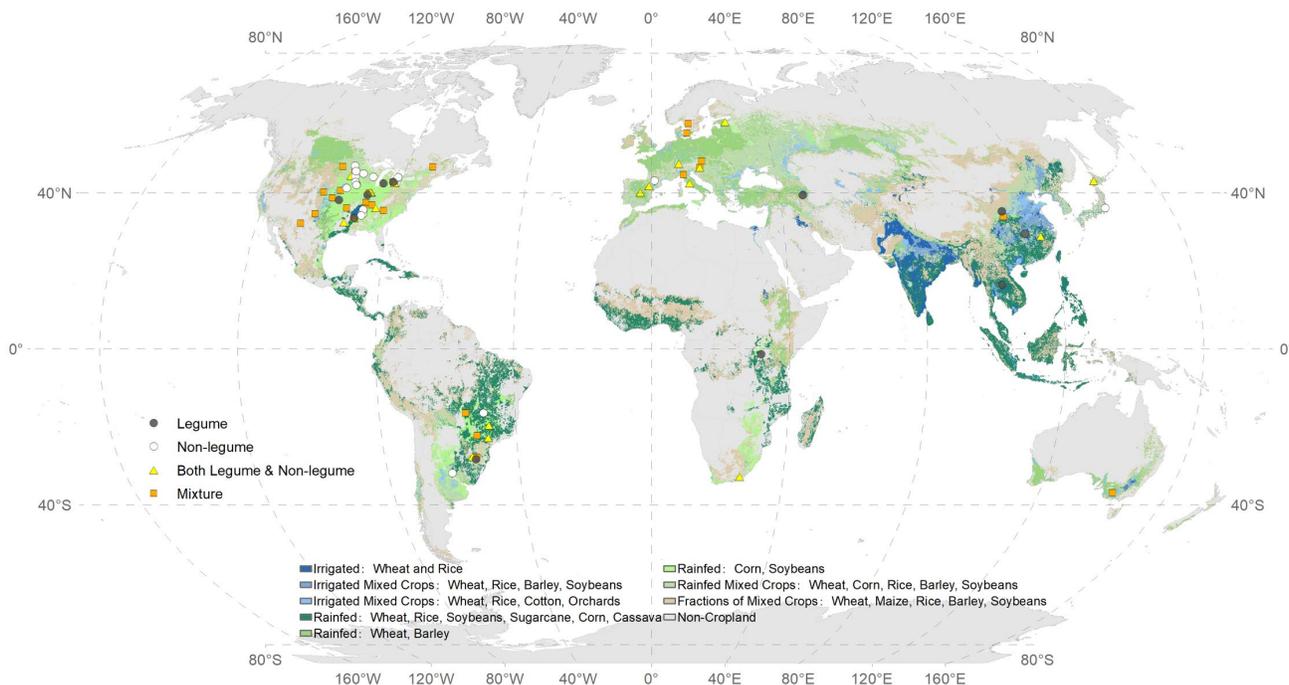
111 The literature survey process comprises the steps of “Identification”, “Screening”, “Eligibility”, and
112 “Inclusion” to extract yield data from both the Web of Science and the Google Scholar databases. Two
113 keywords “yield” and “cover crop” were used to query the databases and identify literature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

122 After screening a total of 2,904 articles from the Web of Science and the Google Scholar databases,

123 we identified 104 publications that meet our criteria, resulting in 1,027 yield records for meta-analysis.
124 All the raw yield records are accessible through Table S1. The yield dataset consists of 3,881 replicated
125 experiments conducted across 20 countries worldwide (Fig. 1). These yield data were either obtained
126 directly from tables or extracted from graphs using WebPlotDigitizer (Rohatgi, 2015). In conjunction with
127 the yield data, additional supplementary details were collected and associated with relevant crop yield
128 records, including experimental site location, cover crop and main crop species, duration of cover cropping,
129 field physical factors (i.e., soil texture, precipitation, temperature), and field management practices (i.e.,
130 rotation, N fertilizer inputs, irrigation, and tillage). This comprehensive dataset was built to detect crop
131 yield variation under different cover cropping scenarios such as utilizing cover crops combined with
132 tillage/no-tillage, fertilized/unfertilized, and drylands/non-drylands. Each independent record was
133 regarded as a basic meta-analysis unit.

134 Within these supplementary details, all the management practices such as tillage, fertilization, and
135 irrigation refer to operations performed on the main crops. To maintain yield data independence in our
136 analyses, we only used one pair of yield data as independent records. There were cases in which several
137 yield data points were extracted from the same publication when multiple practices such as cover crop
138 types, tillage, fertilization, and irrigation were implemented. All the cover crop species were grouped into
139 three types: leguminous, non-leguminous, and mixture. Corn, soybean, and wheat were the major main
140 crop species included in the database; crops such as sorghum, rice, and barley were categorized as others.
141 As was done in a previous global-scale meta-analysis (Daryanto *et al.*, 2017b), soil texture was grouped
142 into fine texture (clay, clay-loam), medium texture (loam, silt-loam, silty-clay-loam), and coarse texture
143 (loam-sandy, sand, and sandy-loam). Since precipitation information is not reported in some publications,
144 we extracted the aridity index (AI) from the Global Aridity Index and Potential Evapotranspiration
145 Database (Trabucco and Zomer, 2018) using the coordinates of each study site and AI as a reference
146 indicator of moisture condition (Yu *et al.*, 2021; Zomer *et al.*, 2022). Areas with $AI > 0.65$ were defined
147 as non-drylands (Wang *et al.*, 2012; Wang *et al.*, 2022). For cover cropping duration, if a study reports
148 main crop yield data in a continuous time series, the yield of each year was recorded separately with an

149 indication of cover cropping duration (e.g., 1-4 years) in the dataset.



150

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

153 2.2 Meta-analysis

154 To quantify the impacts of cover crops on yield in different settings, meta-analysis was used to
155 construct the confidence intervals for each of the aforementioned categorical variables. Here, we chose to
156 use the response ratio as the effect size index in the meta-analysis, which is defined as the ratio of the
157 experimental group (i.e., with cover crop) mean and control group (i.e., without cover crop) mean. In this
158 study, yield varied significantly due to differences in main crop species and growing conditions.
159 Consequently, the collected yield data exhibited a skewed distribution. To achieve a normal distribution
160 of yield response ratio, we denoted the natural logarithm-transformed response ratio ($\ln R$) to represent
161 the metric quantifying the relationship between experimental and control groups (Hedges *et al.*, 1999).
162 $\ln R$ was computed as:

$$163 \ln R = \ln(\bar{X}_E) - \ln(\bar{X}_C) \quad (1)$$

164 where \bar{X}_E and \bar{X}_C represent the average yield of experimental group data and control group data,
165 respectively.

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

$$173 \quad v_{lnR} = \frac{(SD_E)^2}{n_E \bar{X}_E^2} + \frac{(SD_C)^2}{n_C \bar{X}_C^2} \quad (2)$$

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

$$179 \quad \bar{\theta} = \frac{\sum W_i \theta_i}{\sum W_i} \quad (3)$$

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

181 Bootstrapped confidence limits were determined using the statistical software MetaWin 3.0
182 (Rosenberg *et al.*, 1997). Bootstrapping was iterated 9,999 times to calculate a 95% confidence interval
183 (CI) around the cumulative mean effect size for each categorical variable. If the estimated range within
184 95% CI is larger than zero, it indicates that cover crops positively impacted the main crop yield, and vice
185 versa. The yield impact was considered not significant (no statistical difference between cover cropping
186 and no-cover cropping) when the estimated 95% CI overlaps zero. The forest plot with the error bar was
187 drawn using GraphPad Prism 9.0. To present the magnitude of the effect of cover crops relative to without

188 cover crops , the percentage change of the effect size was calculated using equation (4):

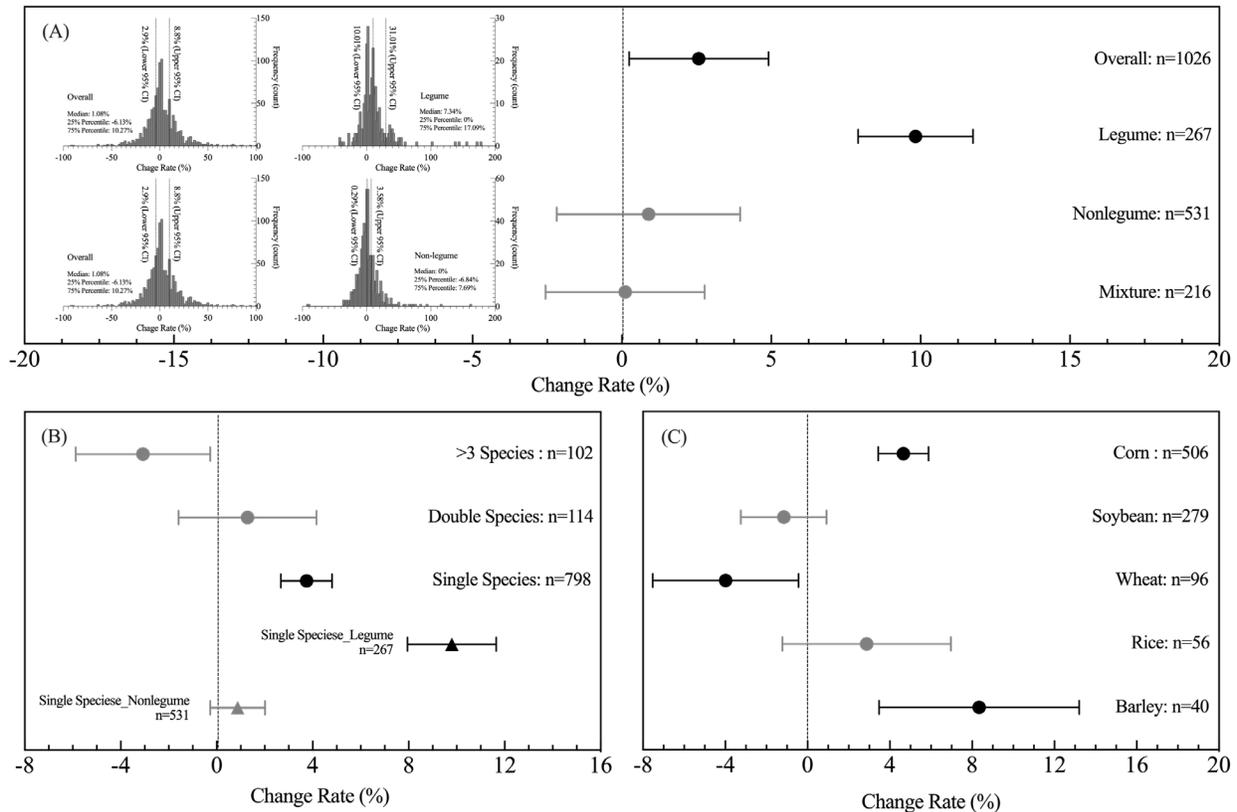
$$189 \quad \text{Change Rate (\%)} = (e^{\ln R} - 1) \times 100\% \quad (4)$$

190 **3. Results**

191 *3.1 Overall cover crop impacts*

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

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

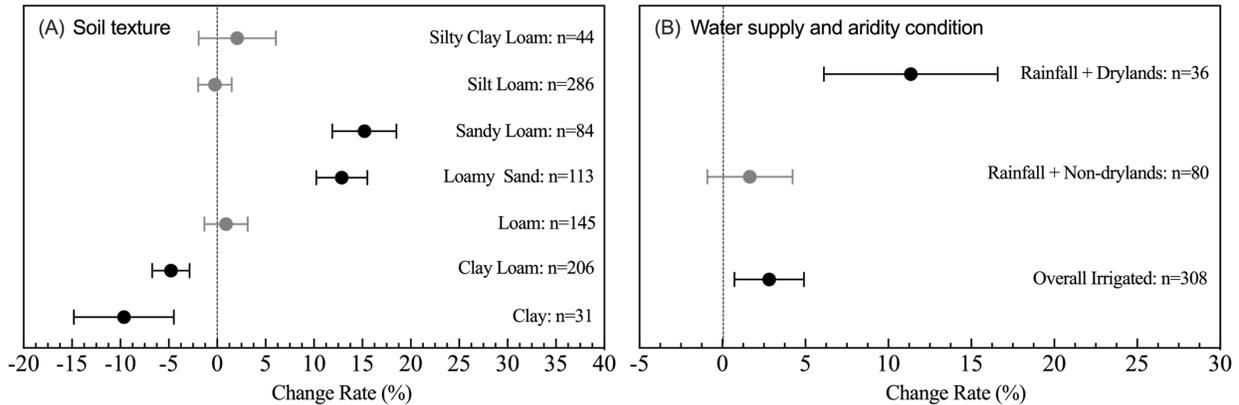


209
 210 Fig. 2. Yield variation and frequency distribution under different types of cover crops (A), yield variation under different
 211 numbers of cover crop species (B), and yield variation under different types of main crops (C). Black dots represent the mean
 212 $\ln R$ with the error bar indicating the 95% CI. The letter “n” indicates the number of records involved in the calculation. P-
 213 values are less than 0.05 in all the above figures. The gray bars indicate the estimated 95% CIs overlap with zero.

214 **3.2 Impacts of physical conditions and management practices**

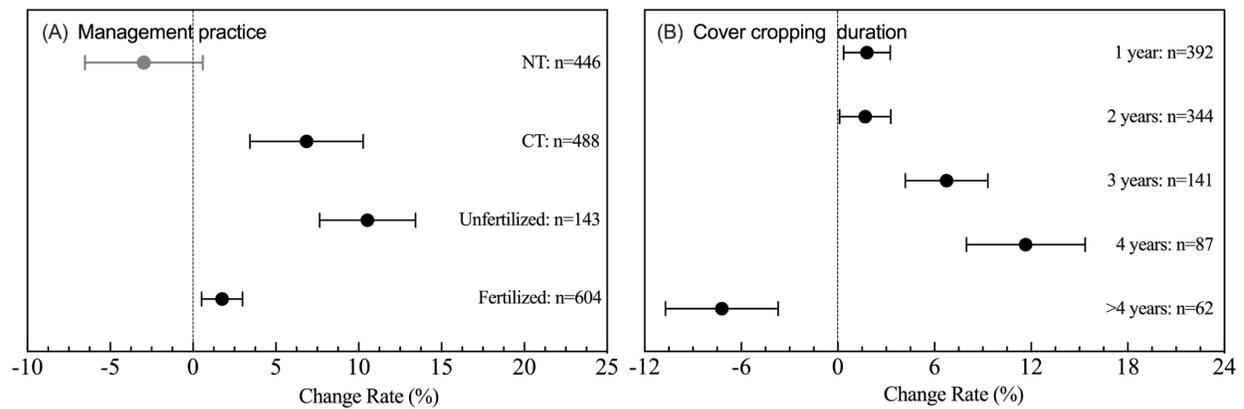
215 Soil texture and climate conditions were examined as physical factors affecting yield response. Soil
 216 texture is known to affect yield through its impact on soil water and nutrient availability. Overall, cover
 217 crops increased yield by 12.9% and 15.2%, respectively in loamy sand and sandy loam soil (coarse-
 218 textured). In contrast, in fine-textured soils, the practice induced a main crop yield reduction of 4.8% and
 219 9.6% in clay-loam and clay soils, respectively (Fig. 3A). For soils with high silt content (silty clay, silty
 220 clay loam, loam), no significant impact on main crop yield was found (CI overlapped with zero). We also
 221 examined the yield response to cover cropping under different moisture conditions (excluding
 222 irrigation) and found a yield increase of 11.4% for cover cropping in drylands under rainfed
 223 conditions (Fig. 3B). The effect size bias was low considering heterogeneity being minimal ($I^2 <$

224 10%). As for non-drylands under rainfed conditions, the 95% CI overlapped with zero, indicating no
 225 significant impact of cover cropping on yield. Moderate heterogeneity was reported with I^2 less than
 226 50% based on the Chi-squared statistic.



227
 228 Fig. 3. Main crop yield responses to soil texture (A) and water supply and aridity condition (B). Black dots represent the mean
 229 lnR with the error bar indicating the 95% CI. The letter “n” indicates the records number of records involved in the calculation.
 230 P-values are less than 0.05 in all the above figures. The gray bars indicate the estimated 95% CIs overlap with zero.

231 The effect of management practices (tillage, fertilizer application, duration of cover cropping) was
 232 examined. Results showed that cover cropping plus conventional tillage (CT) resulted in a 6.9% increase
 233 (Fig. 4A), whereas cover cropping plus no-till (NT) had no statistically significant impact on main crop
 234 yield (95% CI overlapped with zero). A 10.5% yield increase was observed when cover cropping was
 235 implemented without fertilizer, but the yield increase was only 1.8% when cover cropping was combined
 236 with fertilizer treatment. These results provided evidence that cover crops are most beneficial under
 237 nutrient-limited conditions. Overall, main crop yield increased with a longer duration of cover cropping.
 238 The main crop yield increase grew from 1.8-1.9% during the first two years of cover cropping to 6.7%
 239 and 11.6% after three and four years of cover cropping, respectively (Fig. 4B). Interestingly, no yield
 240 increase was observed after five years, and a yield reduction of -7.2% was recorded with duration > 4
 241 years.



242

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

246 **4. Discussion**

247 Cover cropping provides an opportunity to benefit both food security and climate. The primary
 248 obstacle to the widespread adoption of cover crops is the concern of a decreasing yield of main crops. Our
 249 analysis aims to determine the extent to which cover crops impact the yields of main crops. Furthermore,
 250 we aim to identify conditions under which yield penalties can be minimized and yield benefits can be
 251 maximized. Our analysis indicates a modest yield increase after the adoption of cover crops across global
 252 cases. Specifically, we estimated an overall yield increase of 2.6%. Such results are consistent with prior
 253 research. A newly published meta-analysis reported cover cropping simultaneously increased yields and
 254 SOC in 59.7% of 434 paired observations globally (Vendig *et al.*, 2023). Given that cover crops are often
 255 utilized in conjunction with other management practices and occur across various meteorological and soil
 256 conditions, we further identified the specific conditions that promote or reduce yield, as well as the
 257 underlying mechanisms.

258 *4.1 Yield enhancement scenarios*

259 Yield variability by cover cropping is a trade-off between providing soil ecological services and
 260 depleting N and soil moisture for the main crop. We observed legume cover crops, coarse soil texture,

261 dryland areas, and longer cover cropping duration were the scenarios that would lead to yield enhancement.
262 Considering the interaction of mineral fertilizer with the N-fixing ability of cover crops, tillage practice
263 with soil texture, and irrigation with aridity conditions, we discussed the optimal scenarios that can
264 maximize the yield-promoting effect.

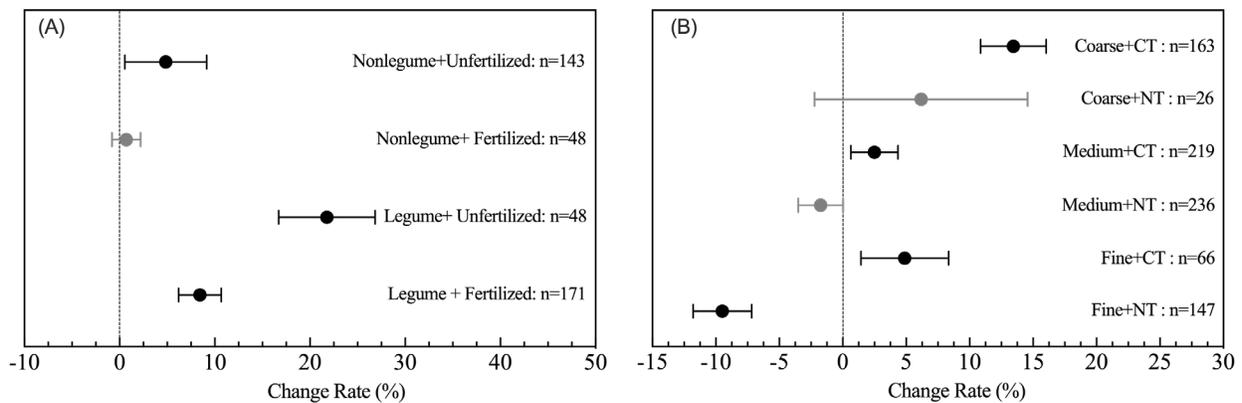
265 Commonly recognized as beneficial to subsequent crop yield, N-fixing leguminous cover crops such
266 as vetch and clover can enhance N inputs derived from atmospheric N via biological N fixation (Kakraliya
267 et al., 2018). The use of winter leguminous cover crops for erosion control and to provide additional N to
268 the soil is well-established (Torbert et al., 1996). It is not surprising to observe better yield performance
269 by leguminous cover crops compared to non-leguminous cover crops (Fig. 2A). However, fertilization
270 tends to negate the positive yield effects of leguminous cover crops. We noticed the leguminous cover
271 crop yield increase is 13.4% lower with fertilization than without fertilizer use (Fig. 5A). This is not to
272 say that fertilizing main crops will result in lower yields. The use of leguminous cover crops can fix N and
273 further lead to yield-increasing benefits compared with no-cover cropping when the main crops are not
274 fertilized. This finding corroborates with previous quantitative synthesis and meta-analysis (Miguez and
275 Bollero, 2005; Daryanto et al., 2018). Liebig's law explains this, that is, the yield of plants is limited by
276 the element in the least available quantity (Chapin et al., 2002). Specifically here, in actual field practice,
277 excessive N is usually added through fertilization (thus removing the limitation), other resources such as
278 water and temperature may become limiting factors for the main crop yield as suggested by Qin *et al.*
279 (2021). Referring to cover cropping without fertilization, leguminous cover crops (21.8%) resulted in a
280 higher yield increase than non-legumes (4.9%). Evidence from Montana also supported these results.
281 Miller *et al.* (2023) found that fertilized wheat under cover cropping is often susceptible to “haying off”
282 and leads to lower yield than cover cropping-only practice. The interpretation is that during the grain fill
283 period, fertilization maintaining vigorous early wheat biomass production consumes too much water,
284 resulting in reduced harvest index and grain mass (Herwaarden *et al.*, 1998). Slightly different from our
285 expectation is that leguminous cover crops induced a greater yield increase (8.4%) compared to non-
286 legume under fertilizer treatment (Fig. 5A). One possible explanation is that improper fertilization

287 strategies (e.g., timing of N application) lead to N loss through leaching and runoff before N uptake by
288 the main crops. Legume cover crops can slowly release nutrients (including fixed N) from decomposing
289 biomass and remain effective in boosting yield compared to non-legumes.

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

312 Introducing cover crops in dryland regions is another yield enhancement scenario if precipitation or

313 irrigation can replenish soil water consumption by cover crops. After cover crop termination, the biomass
 314 remaining on the soil surface acts as a protective cover to conserve soil moisture (Hoyt and Hargrove,
 315 1986). Besides, cover cropping also benefits from improving soil aggregation, aeration, water infiltration,
 316 and nutrient uptake by the live roots in wetter years (Blanco-Canqui, 2018; Rosa *et al.*, 2019). A two-year
 317 experiment in New Mexico suggests cover crops can be successfully grown under limited water
 318 availability in irrigated arid systems of New Mexico while still improving soil quality (Agarwal *et al.*,
 319 2022). Our results corroborate this. Adopting cover crops in drylands under rainfed conditions led to an
 320 11.4% yield increase, while no statistically significant yield impact under cover cropping in non-drylands
 321 (Fig. 3B). For this instance, cover cropping can be regarded as a low-cost alternative to irrigation (Delgado
 322 *et al.*, 2007). Bayala *et al.* (2012) proposed a precipitation threshold for these different impacts. When
 323 annual precipitation is below 600 mm, cover crops are generally more beneficial to main crop yield than
 324 other conservation agriculture practices in drylands. Garba *et al.* (2022) indicated that 700 mm represents
 325 a switch point to achieve significant main crop yield benefits of cover cropping in drylands. However,
 326 cover cropping plus non-irrigation should be adopted with caution especially when moisture conditions
 327 are low and approach the main crop water stress point.

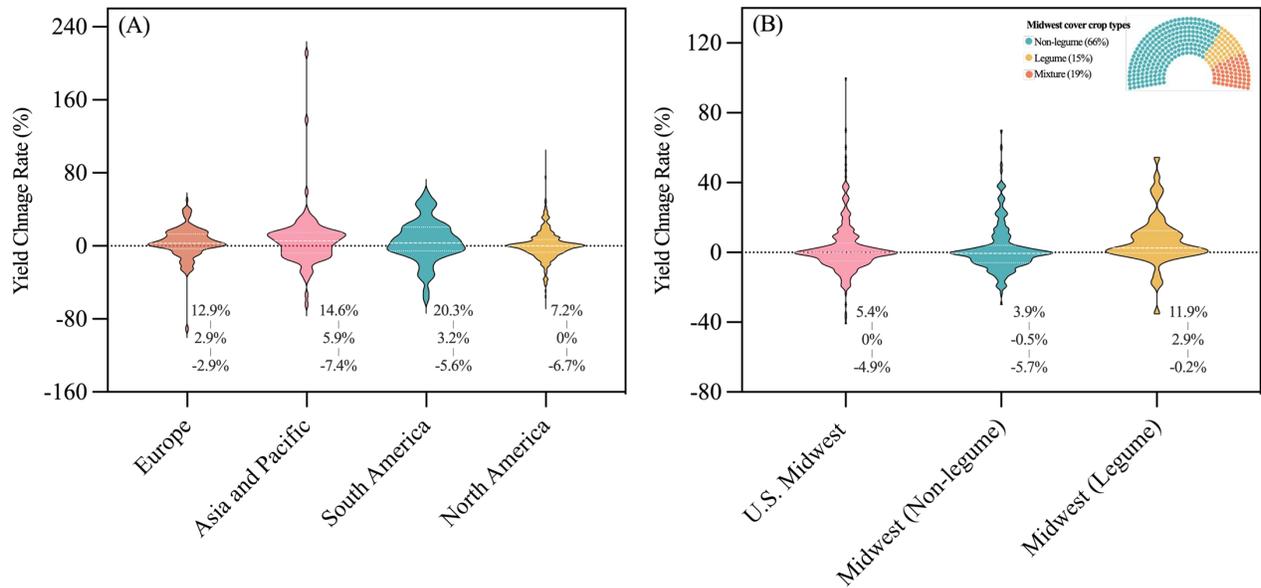


328
 329 Fig. 5. Main crop yield response to combined effects of cover crops with fertilization (A), different soil texture and tillage
 330 combination (B). Black dots represent the mean lnR with the error bar representing the 95% CI. Letter n indicates the number of
 331 records. The p-values indicate the statistical differences between various groups, and in both figures, these values are less
 332 than 0.05. The gray bars indicate the estimated range within 95% CIs overlap zero.

333 4.2 Yield impairing scenarios

334 Cover crops are yield-effective in some cropping systems and environments, but not under all
335 conditions. Each cover crop has limitations that may impair yields. Some of these limitations directly
336 cause a decrease in yield, while others reduce the effect of yield enhancement. It is important to understand
337 these limitations to comprehensively understand the yield effects of cover cropping. Cover cropping in
338 fine-textured soils and with more than 10 years of duration represents conditions under non-legume cover
339 crops that are more likely to impair crop yield than to induce yield benefits.

340 We examined several variables controlling crop yield across different continents and observed that
341 the general response was positive, noting a median yield increase of 6.1%. In North America, the median
342 yield increase of cover crops was 1.2%, which was relatively modest compared with Europe, Asia and the
343 Pacific, and South America (Fig. 6A). These results are somewhat different from those of some prior
344 studies. For example, Deines *et al.* (2022) reported that cover cropping had led to a 5.5% yield loss on
345 corn using validated satellite data products across the U.S. Midwest region. Yet, when zooming into the
346 Midwest using our dataset, we found that the effect of cover crops on crop yields is neutral in this region,
347 which is lower than the average effect in North America. The median yield values for legume and non-
348 legume cover crops in the Midwest were 2.9% and -0.5%, respectively (Fig. 6B). The meta-analysis results
349 indicated that legume cover crops had a positive yield increase (4.9%) while non-legume has no impact
350 on yield in Midwest. The non-favorable yield impact of non-legumes was also observed in other crops.
351 For example, Abdalla *et al.* (2019) conducted a meta-analysis and found that non-leguminous cover crops
352 resulted in a greater reduction of cereal yield compared to legumes, with an average loss of 4.0%. About
353 66% of the cover crops in our analysis are non-leguminous and only 15% are leguminous. The dominant
354 non-legume cover crops in corn-soybean rotations in the Midwest region likely resulted in the yield loss
355 observed in Deines *et al.* (2022).



356

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

360 Previous work has pointed out the risk of yield loss in main crops due to cover crop plus NT for a
 361 short duration (Pittelkow *et al.*, 2015). Brouder and Gomez-Macpherson (2014) pointed out that increased
 362 soil compaction under NT may have a direct effect on the risk. Besides, conservation practices such as
 363 cover cropping and NT, when combined, may increase the weed and pest pressure in the short term
 364 (Mashingaidze *et al.*, 2012; Su *et al.*, 2021). Moreover, the beneficial soil properties from cover crops and
 365 NT (increases in soil C, aggregate stability, and available water capacity) take time to develop (Kumar *et al.*,
 366 2012; Pittelkow *et al.*, 2015). As such, it is not surprising to observe that cover crops plus NT show
 367 non-significant effect on crop yield compared with cover crops plus CT, especially considering that 68%
 368 of the data included in this analysis were from short-term experiments of 1-4 years of duration (Fig. 4A).
 369 We suggest that NT duration should be identified as an influential variable controlling cover cropping
 370 benefits. Adopting other management practices such as weed control and soil compaction alleviation could
 371 be considered to shorten the period of yield penalty when cover cropping and NT are implemented in
 372 tandem. Further, the duration of NT implementation before introduction of cover cropping also appears to
 373 have an effect. Blanco-Canqui and Jasa (2019) conducted a 15-year-long field experiment and suggested

374 that introducing cover crops to long-term continuous NT fields may have smaller or slower benefits
375 compared to short-term NT or intensive tillage before cover cropping. We need to point out that, when
376 considering the combined effect of NT and cover crops, soil texture should be considered in the discussion.
377 Upon our closer inspection, cover crop plus NT resulted in a 9.5% yield reduction in fine-textured soils
378 compared with positive yield returns under cover cropping plus CT (Fig. 5B). Regarding the lag period of
379 cover cropping and NT, fine-textured soils are more susceptible to compaction (Hatten and Liles, 2019).
380 Besides, fine-textured soil with high water-holding capacity may offset the benefit of improved water
381 infiltration and greater soil moisture by cover cropping and NT (Serraj and Siddique, 2012), which leads
382 to slower development of other additional benefits such as increasing SOC than medium- or coarse-
383 textured soils (Rawls *et al.*, 2004b). We suggest extra attention should be paid and additional management
384 should be adopted when implementing NT plus cover crops in fine-textured soils to avoid yield penalties,
385 especially in the early years of cover cropping implementation.

386 As for cover cropping duration, prior studies and surveys reported improvements in major crop yields
387 and soil properties over time (Blanco-Canqui and Jasa, 2019; CTIC, 2022). Our findings on short-term
388 durations (shorter than 5 years) suggest that cover cropping leads to year-to-year yield increases (Fig. 3B).
389 Yet, the yield reduction observed with long-term cover cropping (longer than 5 years) was contrary to our
390 expectation. However, given the relatively small sample size and high heterogeneity of this data subset,
391 these results should be interpreted with caution. Nonetheless, such a reduction calls attention to the
392 potential risk of yield penalty from decades of cover cropping. Although decades-long cover cropping
393 research is not common, available information seems to indicate a weakening effect of long-term cover
394 cropping on soil properties and crop yield improvement. A long-term field experiment in Nebraska
395 indicated that, while the positive effects of leguminous cover crops on soil properties disappeared, grass
396 cover crops continue to have a stronger impact on soil properties after twelve years of cover cropping
397 (Blanco-Canqui and Jasa, 2019). A ten-year study across 39 sites in Iowa suggested no significant
398 improvement in main crop yield attributable to the use of cover crops, although cover crops reduced soil
399 erosion and nutrient loss in runoff (Comito *et al.*, 2020). One possible explanation is that the requirement

400 for additional machinery to sow cover crops led to increased soil compaction. Planters and spreaders
401 usually require at least two additional trips into the cover-cropped fields in the Midwest, thereby increasing
402 the risk of compaction. Additionally, in long cover cropping duration, grazing on cover crops by livestock
403 may also result in surface soil compaction due to excessive trampling, potentially suppressing subsequent
404 crop growth (Obour *et al.*, 2021), although this is not commonly highlighted as a major concern.

405 *4.3 Yield variability synthesis*

406 As a management practice within the framework of climate-smart agriculture (CSA), cover cropping
407 is anticipated to enhance crop yield in general (Daryanto *et al.*, 2018; Fan *et al.*, 2021; Van Eerd *et al.*,
408 2023). However, the impact of cover cropping on yield is still debatable. The influence of cover cropping
409 is a consequence of various combined effects, including cover crop species, duration of cover cropping,
410 rainfall, irrigation, fertilization, tillage, and soil texture. It is challenging to draw definitive and general
411 conclusions as to whether cover cropping is beneficial to main crop yield for all cases. Here, we
412 summarized the available data from cover cropping studies conducted across the globe and aimed to
413 synthesize the conditions that are suitable or not suitable for cover cropping.

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

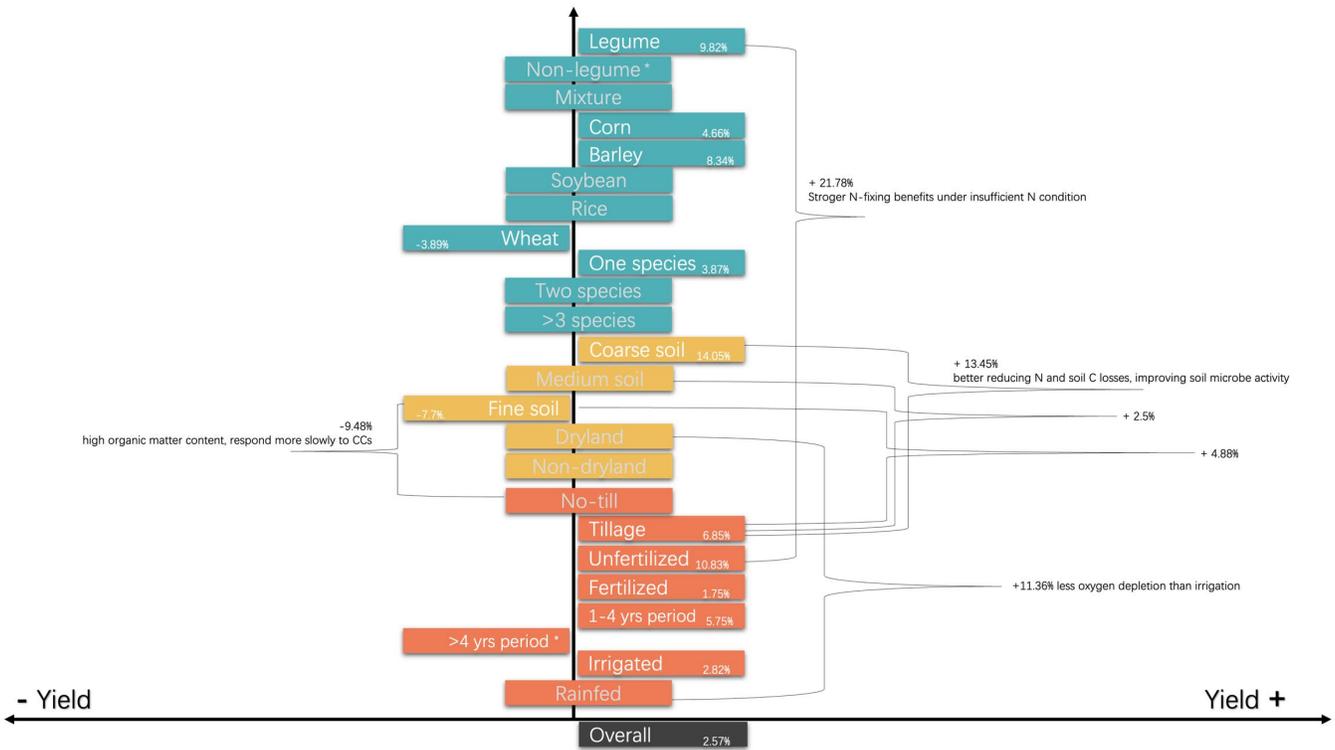
424 Water availability is another important factor determining yield variability. Nielsen *et al.* (2015)

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

445 From a typical farmer's viewpoint, cover cropping is not a zero-sum game. There is a basket of choices
446 that could be chosen to achieve optimal scenarios. For example, adopting CT in fine-textured soils with
447 cover cropping can convert yield reduction to yield increase (Fig. 7). Besides, using leguminous cover
448 crops directly adding soil N input or non-legume cover crops scavenging nutrients for the next subsequent
449 crop can obtain better yield return than relying on mineral fertilizer addition (Fig. 5A). In addition, even
450 when cover cropping is neutral or slightly impairing yields, farmers may still achieve overall positive

451 returns by reducing fertilizer or irrigation expenses and receiving government subsidies. At the current
452 rate in the U.S., a \$5 per hectare subsidy is available for eligible farmers to cover the cover cropping
453 practice (Zhou *et al.*, 2022). Although the amount is small compared with the \$25 cost of seeds and \$12
454 expense of seeding per acre, it helps farmers get through the beginning years of cover cropping before the
455 practice starts to pay off. Our results suggested that more than two years of cover cropping is needed to
456 make it a profitable investment (Fig. 7). Although our findings indicate the general profitability of cover
457 crops, we advise their targeted application for specific purposes rather than attempting to address all field
458 issues. In fields where no-till practices are already established, the primary focus when using cover crops
459 should be on enhancing infiltration, and maximizing N input or N-fixing abilities, rather than solely
460 targeting soil moisture improvement. This is because both no-till and cover crops have similar effects,
461 increasing residue coverage and subsequently reducing soil water evaporation. Additionally, suppose
462 cover crops are aimed to decrease evaporation in dryland areas, the termination time is crucial to avoid
463 soil moisture depletion during the main crop growth period.

464 Given the fact that cover crops affect the yield of subsequent crops is an integrated process influenced
465 by multiple factors, therefore, the variability in the observed impact of cover crops on yield is predictable.
466 A quantitative synthesis of the positive or negative impact of cover crops on crop yield is particularly
467 useful. Clarifying the scenarios that lead to positive yield benefits and helping minimize yield-reducing
468 effects could be highly informative to farmers, farm advisors, and extension services.



469

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

474 **5. Conclusions**

475 This study provides a comprehensive assessment of the impact of cover crops on the yield of the
 476 following main crop through the collection and synthesis of field experimental data at a global scale.
 477 Overall, we observed a moderate yield increase following the adoption of cover crops, but the variability
 478 of crop yield response was substantial. Cover crop type, cover cropping duration, soil texture, and moisture
 479 emerge as important factors that affect yield response. Legume and non-legume cover crops variably affect
 480 the yield outcome of the main crops. Specifically, the legume cover crops type showed the highest yield
 481 increase potential with corn. In coarse-textured soils and under rainfed conditions in drylands, cover crops
 482 tend to improve soil moisture retention and limit nutrient loss, attributes that can translate into crop yield
 483 benefits in these water-limited regions. When implementing cover cropping under no-till (NT) cultivation

484 in fine-texture soils, additional management practices should be adopted to control noxious weeds,
485 alleviate soil compaction, and ultimately avoid yield penalties. These supportive measures could also help
486 shorten the lag period (1-3 years) before the increase in main crop yield can be observed following the
487 initiation of cover cropping.

488

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493

494 **Declarations of interest**

495 None.

496

497

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