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Regionally adapted conservation tillage reduces the risk of crop yield losses: A global meta-analysis

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A R T I C L E I N F O

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A B S T R A C T

Conservation tillage (CS) is a widely implemented and sustainable agricultural practice. Nevertheless, there is substantial controversy regarding its influence on crop yield and the underlying factors that contribute to these effects. We conducted a comprehensive meta-analysis incorporating 5191 comparisons from 551 studies to assess the global crop yield response to CS. The overall findings indicate that CS resulted in a modest reduction in yield, approximately 1.35 % ($P<0.05$), compared to conventional tillage (CT). However, this result varied, with no significant yield difference ($P>0.05$) between CS and CT when strictly following the three principles of CS (no-till, straw mulching, and crop rotation). It should be acknowledged that the relative importance of these three principles varies depending on natural conditions. For example, straw mulching had a greater positive effect in arid regions than no-till and crop rotation. A random forest model analysis identified several influential factors on the relative yield of CS: seasonal precipitation, temperature, soil pH, and no-till duration. For example, CS had negative benefits when seasonal precipitation exceeded 400 mm. Conversely, implementing CS in alkaline soils had significant positive effects (4 %, $P<0.05$). Additionally, the no-till duration did not always yield absolute positive results; no-till durations exceeding 20 years significantly decreased CS yields ($P<0.05$). Prolonged no-till may lead to undesirable consequences such as increased soil bulk density, weed infestation, pest outbreaks, and disease, all of which can adversely affect crop yields; therefore, it is recommended that no-tillage be rotated with conventional tillage to minimize the negative effects of prolonged and sustained no-tillage on yields. Furthermore, CS had greater potential for increasing production in tropical regions. In conclusion, adopting regionally adapted CS practices can minimize the risk of yield reduction. Implementing adaptive CS techniques in specific locations can promote global food security and achieve sustainable agricultural development.

1. Introduction

By 2030, over 840 million people are projected to experience food insecurity and hunger issues (FAO, 2020). This number is expected to rise due to ongoing climate change, public health events like the COVID-19 pandemic, and potential food supply disruptions caused by conflicts (Djekic et al., 2021; Li et al., 2023a; Su et al., 2021a). In an attempt to bridge the gap between food demand and supply, modern agriculture turned to intensive farming methods, but these practices can lead to long-term declines in soil fertility (Lal and Kimble, 1997). Unsustainable agricultural management practices such as excessive fertilizer use, improper irrigation, and intensive tillage practices have detrimental effects on land resources, resulting in severe land degradation and decreased land productivity (Xiao et al., 2020). For instance, in China, the largest developing country, over 19 % of farmland is polluted, and nearly 50 % of farmland faces degradation threats (Chen et al.,

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2014). The conflict between escalating food demand and inadequate land resource productivity has exacerbated, trapped in a vicious cycle (Aggarwal et al., 2019; Corbeels et al., 2020; Xiao et al., 2020). Increasing existing farmland yields in an environmentally friendly and sustainable manner that preserves future food production capacity is crucial for ensuring global food security.

Research has shown that conservation tillage (CS) improves soil quality and promotes sustainable agriculture under most conditions (Blanco-Canqui and Ruis, 2018; Hossain et al., 2020). It is considered a field management practice that improves soil quality by increasing soil carbon sequestration, while appropriate CS ensures crop yields (Lal, 2004; Pittelkow et al., 2015). CS increases soil carbon by increasing carbon inputs from high biomass productivity and reduces carbon losses, leading to a net transfer of carbon from the atmosphere to the soil (estimated at 0.79–1.54 Gt C yr^{-1} globally), which contributes to climate change mitigation (Fuss et al., 2018). As of 2019, the global land area under CS had reached 205.4 million hectares, accounting for 14.7 % of the world's arable land area and expanding by more than 10 million hectares annually (Kassam et al., 2022). CS centers on promoting soil health, maintaining soil productivity, and promoting sustainable agriculture (Chen et al., 2009; Lv et al., 2023). Therefore, the definition of CS is broader, e.g. any tillage practice that maintains at least 30 % of the soil surface covered by residues is considered as conservation tillage (Lal, 1997). Correspondingly, reduced tillage intensity can also be considered as a form of conservation tillage, such as reduced tillage or no-tillage (Alvarez, 2005; Chen et al., 2009; Tebrügge and Düring, 1999). Thus, mulching, reduced tillage or no-tillage can be considered as variants of conservation tillage. Recent studies have shown that crop rotation is also an important factor influencing CS yields. Recent studies have shown that crop rotation is also an important factor in CS yield (Kassam et al., 2022; Zhang et al., 2022). However, in agricultural production, it is often challenging to simultaneously implement all three practices, hence the emergence of combinations of programs that implement one or two CS practices (Zhang et al., 2022). For instance, straw is often used as livestock feed in smallholder farming, making it difficult to implement straw mulching (Valbuena et al., 2012). Similarly, due to lower yields of legumes, rotating food crops with legumes may result in lower overall yields and less acceptance by farmers in food deficit areas (Corbeels et al., 2020). Among the three practices, NT has received increasing attention and has been the focus of CS research (Xiao et al., 2020). However, since crop yield is influenced by multiple interacting factors, including local climate, soil properties, and management practices (Li et al., 2022b), the importance of the three CS practices in increasing crop yields may vary under different climatic conditions. Some studies have suggested that in dry and water-limited areas like the Loess Plateau, straw cover is more important than no-till (Xiao et al., 2019), while in colder regions, straw cover may reduce soil temperature and exacerbate the adverse effects of low temperatures on crops (Li et al., 2022b). However, these conclusions are based on data from specific experimental sites, and it remains unclear whether certain CS practices play a prominent role in other planting areas with varying climate and soil conditions. However, these conclusions are based on data from specific experimental sites, and it is unclear whether certain CS programs play an important role in other regions with different climatic and soil conditions.

Furthermore, the impact of CS on crop yields remains unclear. Some studies have reported that CS practices can increase crop yields (Zhang et al., 2022; Zhao et al., 2017), while others have indicated adverse (Li et al., 2022b) or no effects on crop yields (Shakoor et al., 2021). This variation suggests that the impact of CS on crop yields varies significantly across different environments, and the specific implementation of CS should consider regional adaptability (adapting conservation tillage to local conditions) and appropriate management measures. However, much less is known about the regional adaptation of CS, and ultimately its impact on crop yield. Therefore, it is necessary to identify the main factors affecting CS and evaluate its impact on crop yields based on these regulating factors to enhance our understanding of CS in agricultural sustainability and provide reliable and suitable approaches for implementing CS under diverse agricultural conditions. However, most of the studies have focused on specific experimental sites (specific meteorological and soil conditions), and there is a lack of systematic reports on the specific implementation of CS practices under different meteorological and soil conditions.

Meta-analysis is a powerful statistical tool for summarizing the results of numerous individual experiments while considering the variability among studies (Hedges et al., 1999). In this study, we used a global meta-analysis approach to investigate the effect of CS on crop yield systematically, understand the response of CS crop yield under different environmental conditions, and develop suitable CS combinations tailored to the specific meteorological and soil conditions of different regions. We hypothesized that CS practices adapted to different climatic or soil conditions (optimizing no-till, straw mulching, crop rotation and other field management) could maintain or even exceed crop yields under conventional tillage practices. The specific objectives were (1) to assess the spatial and temporal variability of crop yields under CS, (2) to quantify the effects of environmental factors and management practices on CS yields, and (3) to assess the yield increase potential of different CS practices under different conditions. The results of the study identified the major factors affecting the relative yield of CS, as well as appropriate CS recommendations for different regions, which will contribute to the promotion and application of CS and sustainable agricultural production.

2. Materials and methods

2.1. Data extraction and compilation

We conducted a comprehensive search for peer-reviewed papers on the impact of CS on crop yield. The search was conducted on the Web of Science (http://apps.webofknowledge.com/) and China National Knowledge Infrastructure (http://www.cnki.net/) using the keywords 'no-till or zero-till or no tillage or conservation tillage' and 'yield or yield change' for the years 1980 –2022. At the same time, we incorporated and extended the dataset of Su et al. (2021b)(the dataset of Su had fewer data for the Chinese region, so we supplemented it with a large amount of data for the Chinese region, as shown in Fig. S1). In this meta-analysis, CS (CS in this study consisted mainly of the following tillage practices: NT+M+R, NT+M-R, NT-M+R, NT-M-R and CT+M. NT: no-tillage, CT: conventional tillage, M: straw mulching, R: crop rotation.) was considered the treatment group, while conventional tillage (CT: Rotary tillage with a rotary tiller or ploughing with a plough plate to a depth of 15–25 cm, while removing the straw.) served as the control group. The literature selection process used in this study followed the PRISMA guidelines (Fig. S2) and we applied specific criteria to ensure a high-quality dataset, as follows: (1) field experiments only (excluding lab cultures, greenhouses, and pot experiments); (2) studies comparing CT and CS conducted at the same location, with reported average yields for both systems; (3) information provided on crop rotation, and crop residue management; (4) consideration of multiple observations from the same publication (e.g., multiple years and treatments) as independent data points, provided these observations received different treatments and covered different environmental conditions; (5) implementation of experimental treatments under a replicated experimental design. We used GetData Graph Digitizer (http://www.getdata-graph-digitizer.com/) for digitizing images to obtain values for data presented graphically. Overall, we collected 5191 paired observations from 551 articles by integrating the control and CS treatment data. Fig. 1 illustrates the geographic locations of these studies.

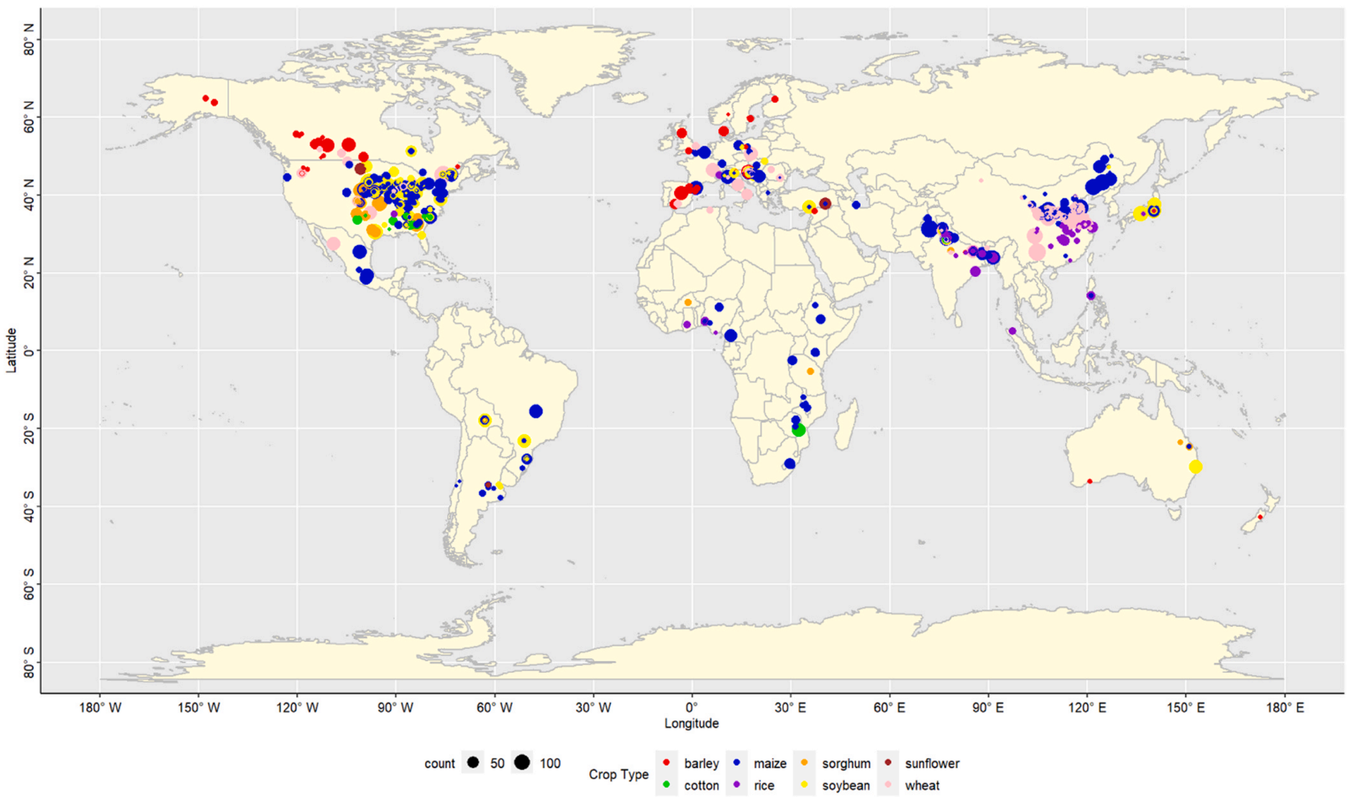

Fig. 1. Location of experimental sites. Circle size reflects the number of observations, while circle color indicates crop type.

2.2. Data analysis

2.2.1. Meta-analysis

In this study, response rate (RR) was calculated as the ratio between the yield (kg ha^{-1}) of treatment (CS) and control (CT). We quantified the magnitude of the effects using the natural logarithmic conversion of the RR of individual observations because they linearize the measurements and provide a positive normal sampling distribution. (Corbeels et al., 2020; Hedges et al., 1999; Li et al., 2023b).

$$\ln RR_i = \ln\left(\frac{x_i^t}{x_i^c}\right) = \ln(x_i^t) - \ln(x_i^c) \tag{1}$$

where $\ln RR_i$ is the effect size of the corresponding parameters from ith comparisons, and x_i^t and x_i^c are the mean values of the treatment and control groups, respectively. We calculated the weight of each response ratio, where the weight is equal to the reciprocal of the variance ($1/v$), to obtain the average effect size ($\ln RR_{++}$). A random-effects model was chosen in MetaWin 3.0 software (Rosenberg, 2024) because the same publication mostly contains multiple observations, data may be non-independent, and coefficient estimates between studies are subject to sampling error (Liu et al., 2023). The weighted average natural logarithm of the response ratio ($\ln RR_{++}$) for each subgroup was calculated using Eq. (2):

$$\ln RR_{++} = \frac{\sum(\ln RR_i \times w_i)}{\sum w_i} \tag{2}$$

where i denotes the ith observation, and $\ln RR_i$ and w_i indicate the effect size and weight of each crop yield comparison, respectively. The variance (v) was estimated as follows:

$$w_i = \frac{1}{v} = \frac{1}{\left(\frac{s_t^2}{n_t x_t^2} + \frac{s_c^2}{n_c x_c^2}\right)} \tag{3}$$

where n_t and s_t are the sample size and standard deviation of the treatment group, and n_c and s_c are the sample size and standard deviation of the control group. Statistical significance was determined by calculating the 95% confidence interval (CI) of $\ln RR_{++}$ using Eq. (4):

$$95\%CI = \ln RR_{++} \pm 1.96 SE_{\ln RR_{++}} \tag{4}$$

where $SE_{\ln RR_{++}}$ is the standard deviation of $\ln RR_{++}$.The effect size and 95 % bootstrap CI were determined using MetaWin 3.0 software. A 95 % CI overlapping zero indicates that CS had no significant effect on the variable. For ease of interpretation, the mean effect size was expressed as a percentage (Lin et al., 2023) using Eq. (5):

$$\left(e^{\ln RR_{++}} - 1\right) \times 100\% \tag{5}$$

A frequency distribution approach was used to assess the quality and variability of yield data. The Gaussian function was used to assess the normal distribution of the observed variables, as follows:

$$y = a \times \left(\frac{-(x - x_0)^2}{2b^2}\right) \tag{6}$$

where x and y represent the mean and frequency of the natural logarithm of ln$R$ for the corresponding interval, and a and b are the coefficient and variance of the frequency distribution, respectively. The normal distribution test of data was carried out using Origin 2023 (study version) software. The funnel plot was used to assess whether each variable was biased in the overall database (Kossmeier et al., 2020). As shown in Fig. S3, the logarithmic yield ratio was symmetrical, indicating the absence of publication bias. Furthermore, in subgroup analyses, the between-group heterogeneity Qb ($P < 0.05$) indicates that explanatory variables in the model explain the large heterogeneity in effect sizes across studies(Zhang et al., 2023). The Qb values of the main explanatory variables considered in this study are shown in Table S1. Finally, we used subgroup analysis to estimate the yield-increasing potential of different conservation tillage in different regions.

2.2.2. Machine learning

We used a machine learning algorithm (Random Forest Model, RF) to identify the main drivers of CS/CT yield (RR, response variable). Random forest is an ensemble learning algorithm that combines numerous individual decision trees constructed from bootstrap datasets. This approach is particularly suitable for small-sample, high-dimensional problems, even in cases where predictor variables are highly correlated. Our analysis calculated the relative importance of 12 predictor variables for relative crop yields in CS using the random forest package for R (version 4.2.0) (Lin et al., 2023; Xu et al., 2022). These variables encompassed climate factors (precipitation and temperature during the crop growing season), soil properties (soil type, pH), and management conditions (crop type, planting years, rotation, straw mulching, CS principle, weeding practices, N input, and no-till duration).

2.2.3. Mean effect of multiple independent variables

First, the natural logarithm of the overall mean CS - to - CT yield ratio was calculated for 5191 observations using a random effects model in MetaWin 3.0 software. Next, the natural logarithm of yield ratio was analyzed for variations with different environmental factors (precipitation, air temperature and pH) and management practices (nitrogen application and no-tillage duration) using the following multiple linear regression model:

$$y = \alpha + \beta 1P + \beta 2T + \beta 3N + \beta 4pH + \beta 5D + \varepsilon \tag{7}$$

where y is the CS yield response ratio, α is the intercept value, P is growing season precipitation (mm), T is growing season temperature (°C), N is N input (kg ha^{-1}), D is no-tillage duration (year), and β1– β5 are the fitting coefficients for each variable.

2.2.4. Relationship between environmental factors and relative CS yield

Linear regression was performed using Origin 2024 (study version) to better understand the relationship between environmental factors (including water, air temperature) and management practices (nitrogen application rate and no-till duration) with CS yield variation.

3. Results

3.1. Temporal and spatial changes of crop yield under CS

Crop yields varied greatly depending on crop type, research area, and planting years (Fig. 2, Fig. S5). The yield frequencies and ln(RR) values for CS crop yield followed Gaussian normal distributions (Fig. 2, Fig. S4), indicating a uniform dataset (Du et al., 2021; Shan and Yan, 2013). The average yields per hectare for global maize, soybean, wheat, rice, barley, sorghum, cotton, and sunflowers were 7844.8, 2615.2, 4151.0, 6687.9, 2915.8, 3856.0, 1321.1, and 1372.5 kg ha^{-1}, respectively (Table S2). Maize, soybean, and wheat had the widest distribution and largest datasets, covering the north temperate, tropical, and south temperate zones. Therefore, we further analyzed maize, soybean, and wheat spatiotemporal distribution characteristics. Due to varying management practices and geographical locations, maize, soybean, and wheat yields significantly differed. Regardless of tillage practice, these three crops had the highest yields in the north temperate zone and the lowest yields in the tropical zone (Fig. S5). We compared yield changes in maize, soybean, and wheat during the 1980s (1981–1990), 1990s (1991–2000), 2000s (2001–2010), and 2010s (2011–2022, grouped as the 2010s due to the small proportion of data in 2021–2022) to evaluate temporal yield changes in different regions under two tillage practices (Fig. S5). Overall, yields increased over time, with the fastest growth in the north temperate zone and the slowest in the tropical zone. The average yield of maize, soybean, and wheat in the north temperate zone increased from 6963.3, 2502.2, and 2259.9 kg ha^{-1} in the 1980s to 9907.8, 3279.7, and 5332.1 kg ha^{-1} in the 2010s, respectively, reflecting increases of 42.3 %, 31.1 %, and 136 %. The trends in yield changes under CT were consistent with those under CS. In particular, the ratio of CS to CT was lowest in the 1990s, and the difference between CS and CT gradually decreased with time, with CS yielding significantly more than CT by the 2010s (Fig. S6a). Overall, according to the analysis of data divided by climatic zones, the yield reduction of CS was the largest (-8.0 %) in the tropical zone, and the smallest (-0.72 %) in the north temperate zone compared to CT (Figs. S5 and S6).

Our analysis by country revealed that Australia, Brazil, Pakistan, Spain, and China produced a greater average CS yield than CT yield. Other countries had lower CS yields than CT yields, but the differences were insignificant (P>0.05, Fig. S7).

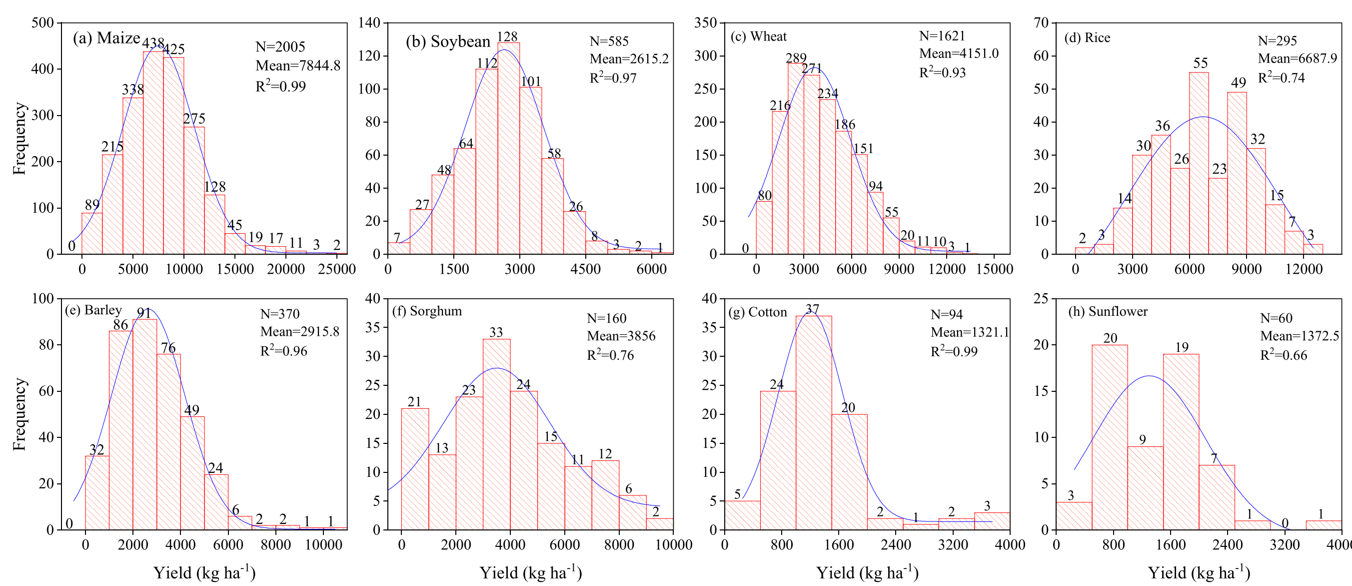

Fig. 2. Frequency distribution of (a) global maize yield, (b) soybean yield, (c) wheat yield, (d) rice yield, (e) barley yield, (f) sorghum yield, (g) cotton yield, and (h) sunflower yield under CS. N, mean, and R^2 are the sample size, average yield (kg ha^{-1}), and the goodness of fit of the Gaussian normal distribution curve to the histogram of the frequency distribution, respectively. The closer R^2 is to 1 means that the histogram of the frequency distribution is more normally distributed.

3.2. Factors affecting CS crop yield change

3.2.1. Influence of meteorological and soil factors

We conducted a random forest analysis to assess the relative importance of 12 potential influencing factors and thus elucidate the driving factors behind crop yield changes under CS (Fig. 3). The most significant factors affecting crop yield for the overall and NT+M (No-till + straw mulching– Conventional tillage) scenarios were precipitation, temperature, soil pH, and continuous no-till duration, for the NT (No-till– Conventional tillage) scenario were weed control, continuous no-till duration, precipitation, and temperature, and for the CT+M (Conventional tillage + straw mulching– Conventional tillage) scenario were precipitation, temperature, soil pH, and soil type (Fig. 3).

Precipitation was identified as the most important factor influencing CS yield, with CS significantly increasing crop yield compared to CT under seasonal precipitation conditions ranging from 0–200 mm and 200–400 mm. The greatest CS yield increase occurred in the 0–200 mm range, with a maximum effect of 10.3 % (CI: 7.3, 13.5, $P<0.05$) (Fig. 4a). However, as precipitation increased, the average effect size of CS relative to CT decreased. When precipitation exceeded 1000 mm, CS had a 6.4 % lower yield than CT (CI: –8.9, –3.8, $P<0.05$) (Fig. 4a).

Temperature was identified as the second most important factor influencing CS yield. Similar to the impact of precipitation, as temperature increased, the average effect size of CS relative to CT decreased. However, CS only had a significantly lower yield than CT when the temperature was above 20°C ($P<0.05$, Fig. 4b). Furthermore, soil pH was another significant factor influencing relative CS yield (Fig. 4c), with the average effect size of CS relative to CT increasing with increasing pH. At pH >7.5, CS had 3.4 % higher yield than CT (CI: 1.8, 5.0, $P<0.05$) (Fig. 4c). In addition to pH, soil type also affected CS yield. Under clay loam and sandy clay loam, CS produced significantly lower yields than CT. However, as the clay content decreased, CS yield tended to increase (Fig. 4d). We further analyzed the effect of CS on soil bulk density, and the results showed that no-tillage in CS significantly increased soil bulk density in the top 0–15 cm of the soil by 4.54 % (Fig. S8). Meanwhile, subgroup analysis showed that CS significantly increased soil bulk density while decreasing crop yield (Fig. 4e).

3.2.2. Effect of no-tillage duration on relative CS yield

We further analyzed the CS dataset centered on no-tillage and showed that no-tillage (NT) duration of CS significantly modulated the effect of CS on crop yield (Fig. 5). In the first two years, CS produced significantly lower crop yields than CT ($P<0.05$, Fig. 5). However, as CS practices continued over a longer period, crop yields gradually increased. By 5–10 years of continuous CS, there were no significant differences in yields compared to CT ($P<0.05$, Fig. 5a). When CS was practiced continuously for 10–20 years, crop yields reached their highest level, 3.3 % higher than CT (CI: 0.9, 6.1, $P<0.05$). Subsequently, CS yields started to decline, reaching their lowest point between 30 and 50 years, at which time they were 8.9 % lower than CT (CI: 13.8, 4.1, $P<0.05$). Notably, the number of observations for studies conducted for >50 years is limited, questioning the significance of these results. The linear regression model indicated a positive correlation between CS duration and CS yield. However, the relative yield observed in our study only slightly increased over time (0.45 % yr^{-1}, Fig. 5b). Thus, while there was an overall positive correlation, subgroup analyses by certain gradients indicated that longer no-till periods did not necessarily lead to a sustained increase in crop yields, but rather a fluctuating process.

3.2.3. Impact of straw mulching and crop rotation

As two important practices of CS, straw mulching and crop rotation significantly affect CS yield (Fig. 6). Overall, the greatest reduction in yield occurred when straw mulching and crop rotation were not used, resulting in a yield decline of –17.3 % (CI: –20.6, −13.9, $P<0.05$). Simultaneously implementing straw mulching and crop rotation minimized the yield decline, with CS yield only 0.98 % lower than CT (CI: –0.55, 2.55, $P>0.05$). Furthermore, when examining the individual effects of straw mulching and crop rotation, we found that straw mulching plays a crucial role in CS yield. Combining CT with straw mulching resulted in the highest yield. In contrast, no-tillage without straw mulching resulted in the lowest yield, 11.0 % lower than CT (CI: –12.6, −9.3, $P<0.05$). However, combining no-tillage with straw mulching significantly reduced the risk of yield reduction, with CS yield only 0.57 % lower than CT (CI: –0.69, 2.10, $P>0.05$) (Fig. 6b). This study incorporated CT+M (conventional tillage + straw mulching) to further compare the relative effects of tillage and straw mulching on CS yield.

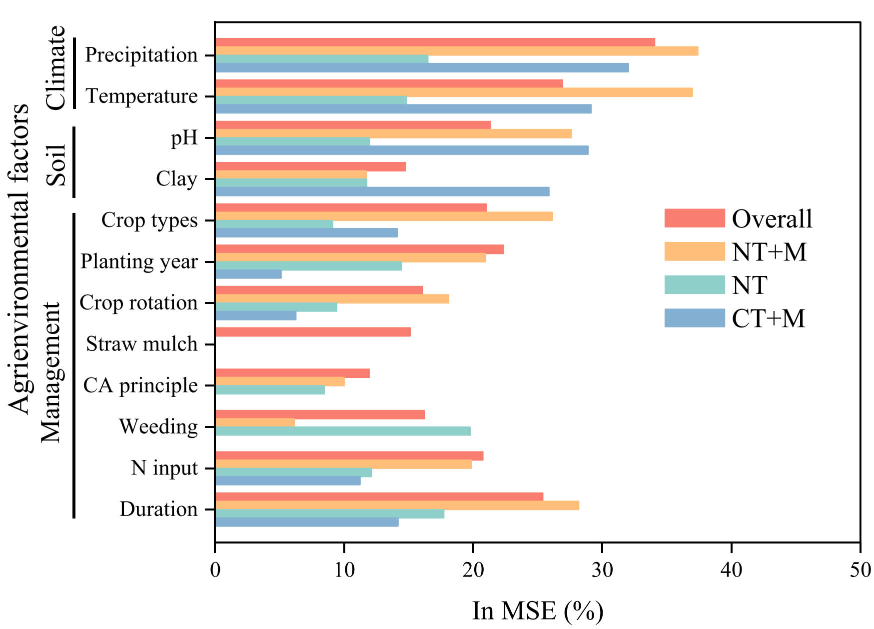

Fig. 3. Random forest modeling predicting the factors affecting crop yield change. Contributions of different agrienvironmental factors to the percentage changes in the responses of yield conservation agriculture practices including overall, No-till + straw mulching (NT+M), no-till (NT) and Conventional tillage + straw mulching (CT+M). The mean square error (MSE) indicates the importance of random forest characteristics in agronomic and environmental factors, higher MSE means more importance. Predicted percentages measure the importance of climate, soil, and agronomic management variables.

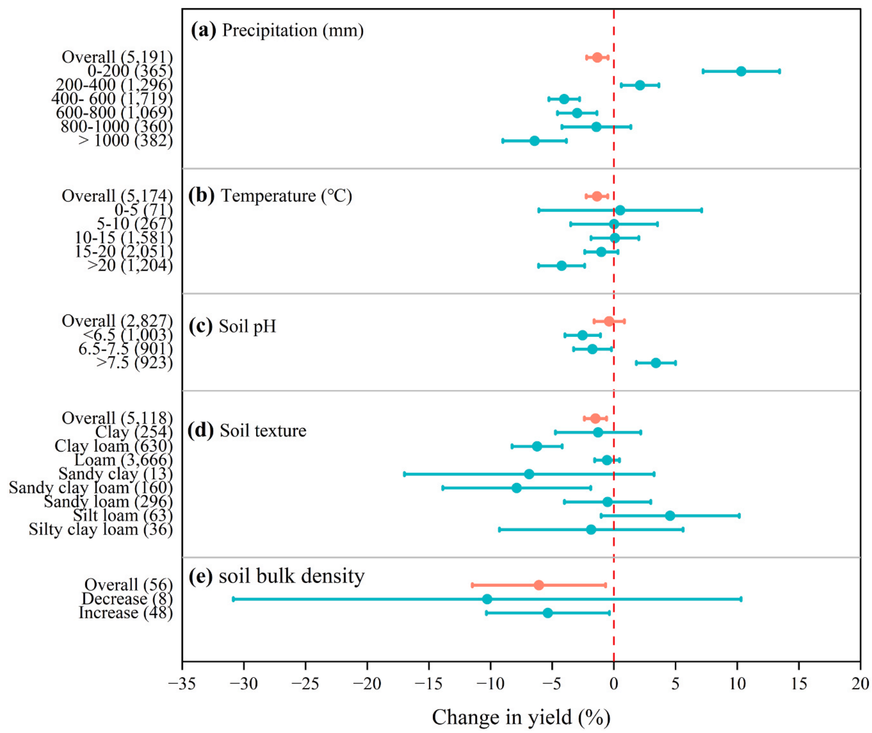

Fig. 4. Relative change in yield in conservation tillage (CS) compared with conventional tillage (CT) segregated by (a) precipitation, (b) air temperature, (c) soil pH, (d) soil type, and (e) change in soil bulk density after CS implementation. Error bars indicate 95 % confidence intervals (CI), with P<0.05 if they do not overlap the zero line. The vertical red dotted line indicates no effect.

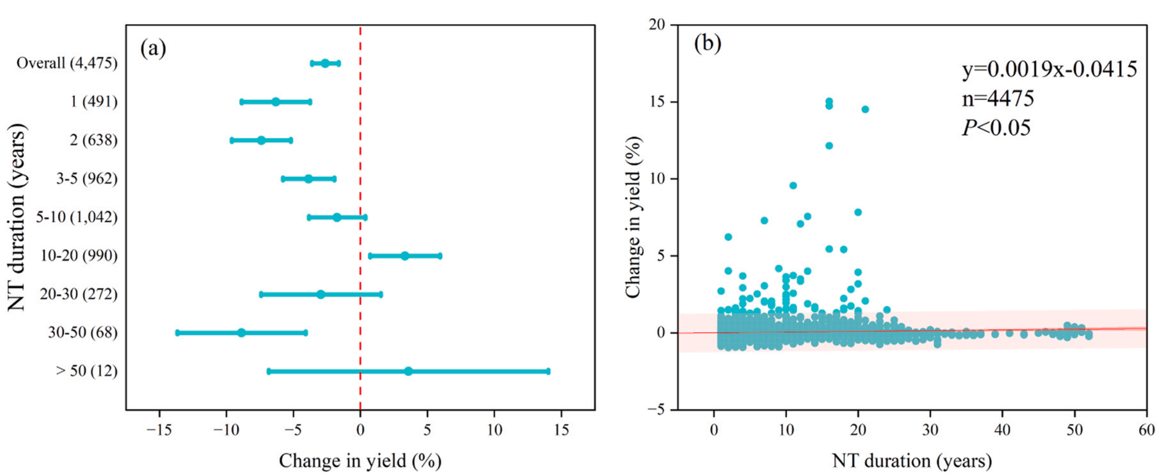

Fig. 5. Relative change in yield in conservation tillage (CS) compared with conventional tillage (CT) segregated by NT duration. (a) Relative yield change at different NT durations, and (b) linear regression model of CS duration and relative change in yield. CS: conservation agriculture; CT: conventional tillage. Numbers in parentheses are the number of observations. Error bars are 95 % confidence intervals, the vertical red dotted line indicates no effect. Effects are significant at P<0.05 when error bars do not overlap zero.

The results demonstrated that CT+M had a more positive effect on CS yield than NT+M (no-till + straw mulching) (Fig. 6b), indicating that in most cases, the yield-increasing effect of straw mulching outweighs that of no-till. The number of crop rotations also emerged as an important factor influencing CS yield. The lowest yield occurred when a single crop was continuously grown, resulting in 7.1 % lower yield than CT (CI: –8.9, –1.2, $P<0.05$). However, when the number of crops rotated reached three, CS had 7.2 % higher yield than CT (CI: 4.4, 10.1, $P<0.05$). Further increasing the number of crop rotations did not continue to increase CS yield, with CS yield decreasing significantly when the number of crops reached four (Fig. 6c).

3.2.4. Effects of weeds, pest control, and nitrogen application on relative CS yield

Conservation tillage can increase weed growth and pest occurrence; however, previous meta-analyses have rarely focused on evaluating the effectiveness of weed control and pest management. Therefore, this study analyzed the impact of different herbicides and insecticides on CS yield (Fig. 7). In the absence of weed control and pest management, CS produced 47.4 % lower yields than CT (CI: –54.2, 39.7, $P<0.05$). Even with manual weeding, CS yield remained 9.3 % lower than CT (CI: –13.5, –4.9, $P<0.05$) (Fig. 7a). However, the use of herbicides significantly increased the relative yield of CS compared to no herbicide use (Fig. 7a). When herbicides and fungicides were used in combination, CS

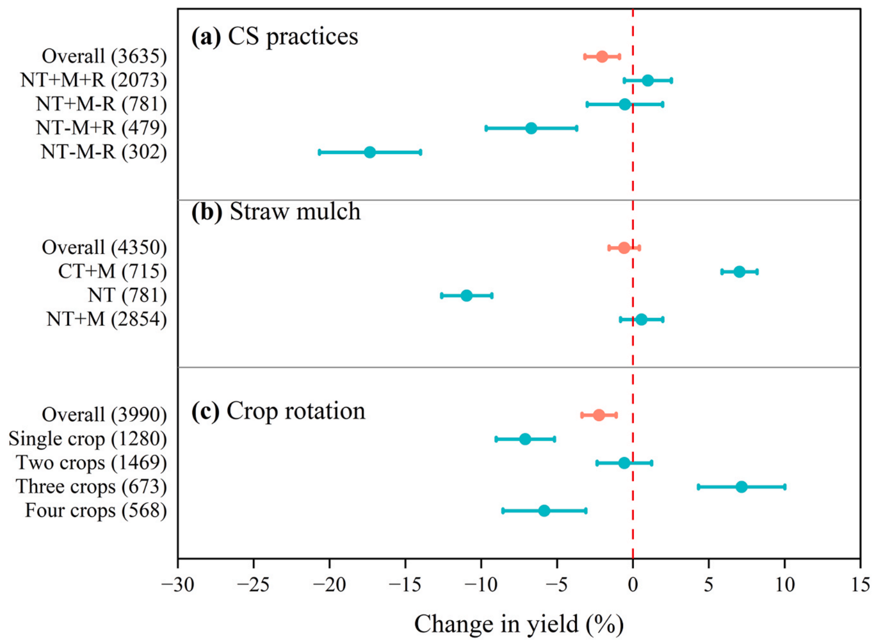

Fig. 6. Relative change in yield in conservation tillage (CS) compared with conventional tillage (CT) segregated by mulching and crop rotation. NT: no-tillage, CT: conventional tillage, M: straw mulching, R: crop rotation. Numbers in parentheses are the number of observations. Error bars are 95 % confidence intervals, the vertical red dotted line indicates no effect. Effects are significant at P<0.05 when error bars do not overlap zero.

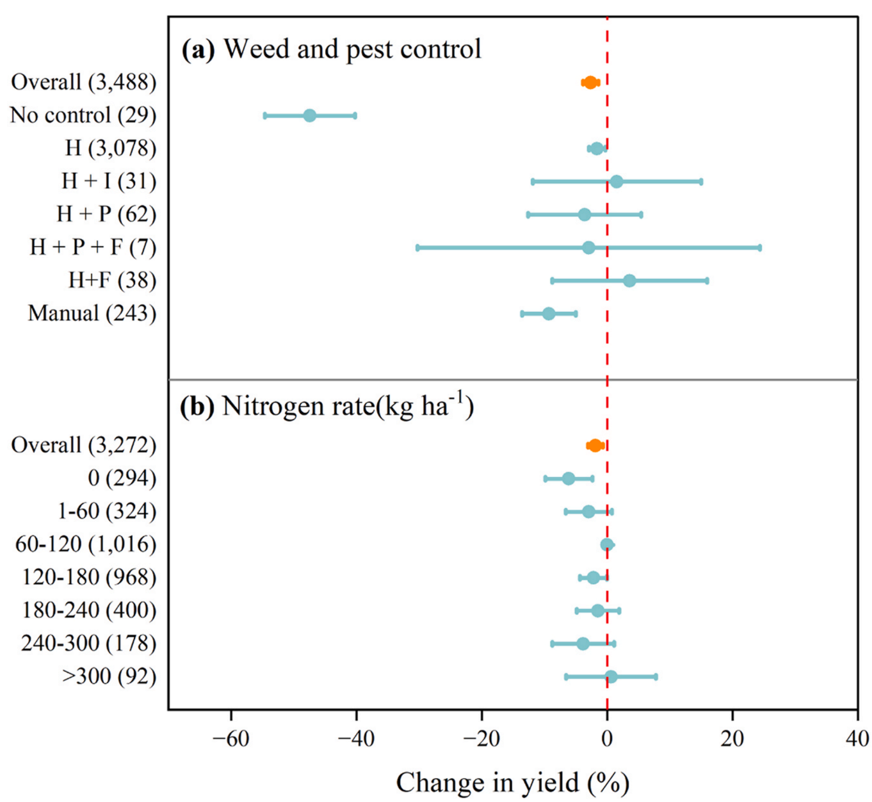

Fig. 7. Relative change in yield in conservation tillage (CS) compared with conventional tillage (CT) segregated by weed and pest control and nitrogen fertilizer application. H: herbicide, I: insecticide, P: pesticide, F: fungicide. Numbers in parentheses are the number of observations. Error bars are 95 % confidence intervals, the vertical red dotted line indicates no effect. Effects are significant at P<0.05 when error bars do not overlap zero.

produced 3.6 % higher yields than CT, but the difference was not significant (P>0.05). Nitrogen fertilizer application positively correlated with relative CS yield (Fig. S9). Only under conditions of no nitrogen application did CS yield significantly decrease compared to CT, with a reduction of –6.1 % (CI: –9.8, –2.3, P<0.05) (Fig. 7b). As nitrogen application increased, the relative yield of CS also increased, and the yield of CS and CT did not significantly differ with nitrogen application (P>0.05).

3.2.5. Effect of crop type on the relative yield of CS

Further analysis of individual crops revealed that sunflowers had a 33.2 % higher yield under CS than CT (CI: 24.4, 42.7, $P<0.05$), while corn had a 3.6 % lower yield under CS than CT (CI: –4.8, –2.5, $P<0.05$). However, the yields of other crops did not significantly differ between CS and CT. Barley, sorghum, and cotton had 2.5 %, 2.6 %, and 0.9 % higher yields under CS than CT, respectively, while rice, soybean, and wheat had 1.3 %, 1.2 %, and 1 % lower yields under CS than CT, respectively ($P>0.05$) (Fig. 8).

3.3. Linkages among predictor variables and crop yield and yield increase potential

Seasonal precipitation emerged as the most influential factor affecting relative CS yield (Fig. 3). Since relative CS yield was negative for precipitation >400 mm (Fig. 4), we divided seasonal precipitation into two categories (0–400 mm and >400 mm). As seasonal precipitation increased, the yield ratio of CS showed a decreasing trend (Fig. S10). Using a multiple linear regression model, we determined the crop yields in the two precipitation gradient categories, with precipitation (Pre), temperature (Tem), nitrogen application rate (N), pH, and no-tillage duration (Duration) as variables (Table 1). The results indicated that nitrogen application rate positively impacted the CS: CT yield ratio when seasonal precipitation exceeded 400 mm ($P<0.05$). When the precipitation was less than 400 mm, precipitation, temperature and nitrogen application amount have a significant negative impact on the yield ratio of CS:CT (Table 1).

Table 2 presents the potential changes in crop yield with different combinations of CS practices across various regions. In the northern temperate zone, selecting the combination with the lowest yield (NT-M-R), representing the most unfavorable practices for crop production in each planting area, significantly decreased crop yield. The worst combination reduced relative crop yield by 18.01 % ($P<0.05$), whereas the optimal CS yield combination increased relative crop yield by 0.78 %. Interestingly, the results highlight that the impact of straw mulching on relative yield outweighs that of crop rotation. Similar trends were observed in the tropical and southern temperate zones. In the tropics, adopting NT+M-R increased relative CS yield by 9.92 %, while NT-M+R only increased it by 2.49 %, compared to NT-M-R. Thus, straw mulching increased yield four-fold more than crop rotation. Overall, the adoption of NT+M+R practices can contribute to sustainable crop production.

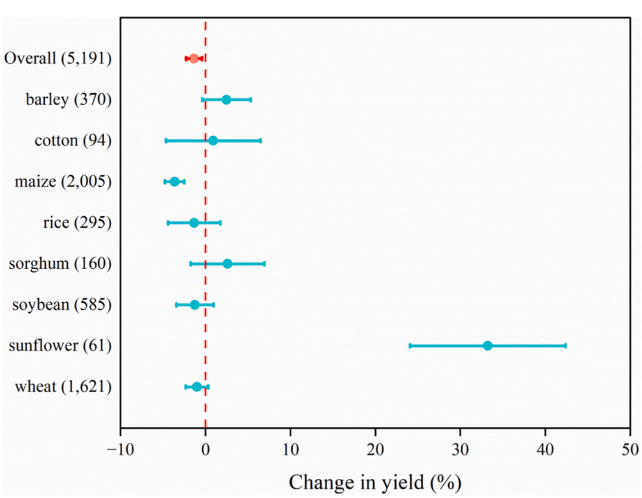

Fig. 8. Relative change in yield in conservation tillage (CS) compared with conventional tillage (CT) segregated by crop types. Numbers in parentheses are the number of observations. Error bars are 95 % confidence intervals, the vertical red dotted line indicates no effect. Effects are significant at P<0.05 when error bars do not overlap zero.

Table 1
Multiple linear regression model of the responses of crop yield to seasonal precipitation (Pre), air temperature (Tem), nitrogen input (N), soil pH (pH), and no-tillage duration (Duration) above precipitation (400+) and below precipitation (400–).

Precipitation(mm)	Items	Value	SE	*t*	*P*
400-	α (Intercept)	0.279	0.1664	1.675	0.094
	β1(Pre)	−0.001	0.0001	−3.621	**<0.001**
	β2(Tem)	−0.021	0.004	−5.603	**<0.001**
	β3(N)	−0.001	0.0001	−3.155	**0.002**
	β4(pH)	0.0448	0.0188	2.382	0.018
	β5(Duration)	0.003	0.0025	1.049	0.295
400+	α (Intercept)	−0.175	0.0811	−2.152	**0.032**
	β1(Pre)	0.0006	0.0003	1.614	0.107
	β2(Tem)	0.0008	0.0018	0.434	0.664
	β3(N)	0.0002	0.0001	1.971	**0.049**
	β4(pH)	−0.001	0.0109	−0.062	0.951
	β5(Duration)	0.0020	0.0014	1.435	0.152

Table 2
Changes in crop yield increase potential using different CS practices in north temperate, tropical, and south temperate zones.

Regions	Different CS practices			
	NT-M-R	NT-M+R	NT+M-R	NT+M+R
North-Temperate (%)	−18.01	−5.57	−0.57	0.78
Tropical (%)	−18.38	−15.89	−8.40	5.43
South-Temperate (%)	−8.26	−3.65	1.75	3.79

Note: Crop yield increase potential refers to the change in CS relative yield when changing from the current worst CS practices to the best CS practices.

4. Discussion

4.1. Overall effect of CS on crop yield

Conservation tillage has gained global recognition as a promising management practice that can significantly improve soil environments (Cooper et al., 2016; Mrabet, 2023; Zhang et al., 2023), including soil structure (Blanco-Canqui and Ruis, 2018; Zhang et al., 2021), water retention (Li et al., 2022a), microbial diversity and activity (Chen et al., 2020; Nugroho et al., 2023), and nutrient availability (Zhang et al., 2018), and thus contribute to increasing crop yields. However, this study showed that, on average, CS reduced crop yields (Fig. 4 and S5), consistent with recent research findings (Pittelkow et al., 2015). Importantly, these adverse effects are not fixed, and the yield performance of CS varies significantly over time and space. During the early 1980s, global soybean, maize, and wheat production under CS were relatively low, primarily due to inadequate fertilizer and herbicide inputs. However, with advances in agriculture, the widespread adoption of crop varieties, herbicides, and pesticides in the 21st century has greatly enhanced the productivity of CS (Fig. S5). Nevertheless, this improvement has been less pronounced in tropical regions, particularly in developing countries such as South Africa, Ethiopia, and Nigeria, where agricultural development and access to fertilizers and herbicides are limited. Consequently, CS yield increases in these regions have been relatively slow. Moreover, the relative yield of CS is also influenced by meteorological factors, soil properties and management measures (Zhao et al., 2017). Therefore, understanding the key ‘driving factors’ that regulate the impact on crop yield can facilitate global promotion and maintenance of crop yields under CS strategies.

4.2. Effects of meteorological and soil factors on the relative production of CS

Seasonal precipitation and temperature are the main factors affecting the relative yield of CS (Fig. 3). Our analysis revealed that the relative yield of CS decreases as seasonal precipitation increases (Fig. 4a and S9), aligning with previous field trial studies (Zhang et al., 2022) and meta-analyses (Xiao et al., 2020) that have shown a negative correlation between crop yield changes and annual precipitation. Straw mulching was particularly important when seasonal precipitation was less than 400 mm, and straw mulching was an important cause of yield increase (Fig. S10b). The presence of straw cover in CS can reduce soil water evaporation, resulting in a positive CS yield effect when water stress occurs during crop growth (Ranaivoson et al., 2017; Su et al., 2021, 2021a; Su et al., 2021, 2021aa). This suggests that CS has the greatest potential for yield improvement in areas experiencing repeated and prolonged droughts. Temperature also negatively affects the relative yield of CS (Fig. 4b), particularly in tropical regions (–8.0 %, $P<0.05$), where smallholder farmers often rely on straw as livestock feed and remove it from fields after harvest (Valbuena et al., 2012). The practice of monoculture with no-till farming in these areas has led to decreased crop yields. This finding is concerning, as tropical regions predominantly include developing countries (Cui et al., 2022), where future food insecurity is expected to worsen with population growth.

Soil type and soil pH are other important factors affecting crop yield (Fig. 3). Soil texture affects crop yield by impacting soil moisture, nutrient availability, and crop root growth (Wei et al., 2022). Although some studies have shown that NT reduces soil bulk density, this study showed that NT significantly increases soil bulk density. Given the small number of literature reporting both yield and soil bulk density in this dataset (56 pairs of data in total), for the reliability of the results, we reextracted the published literature and added an additional 277 pairs of data to support the fact that NT increases soil bulk density (Fig. S8). In this study, the use of CS in clay loam and sandy clay loam soils significantly reduced crop yield (Fig. 4d). This may be due to the fact that CS (especially NT) has the potential to result in a soil surface layer with high soil penetration resistance and soil bulk density (Fig. S8), which can reduce root extension and inhibit normal root growth, adversely affecting yields (Li et al., 2020; Ren et al., 2018). We also showed that CS can achieve higher yields under alkaline soil conditions (Fig. 4c), which may be related to the ability of CS to lower soil pH. A previous meta-analysis found that combining NT with crop residue return significantly reduced soil pH (Zhao et al., 2022). This reduction is associated with increased soil nutrient content during plant residue decomposition, which decreases the alkaline cation concentration and increases H^+ concentration (Zhao et al., 2022). Therefore, implementing CS in alkaline soils can create more favorable soil conditions for crop growth by lowering soil pH. This finding holds promise for improving saline-alkali land.

4.3. Effect of management factors on the relative yield of CS

Straw mulching and crop rotation are important components of CS practices. Straw mulching has positive effects on crop yield by reducing temperature fluctuations caused by external factors such as reducing daytime soil temperature rises and nighttime temperature drops (Chen et al., 2007) and mitigating heat stress by increasing reflectivity and lowering thermal conductivity at the soil surface to reduce soil temperatures significantly (Lu et al., 2015). In most cases, we found that straw mulching had a more significant positive effect on yield than no-tillage (Fig. 6b). We also found that crop rotation can reduce the risk of yield reduction in CS (Fig. 6c). The positive effects of crop rotation on CS include reducing weeds and pests and providing soil nutrient supply (He et al., 2019; Yang et al., 2023). This is crucial for CS practice because CS reduces tillage frequency and increases the likelihood of weed and pest occurrence (Pittelkow et al., 2015). However, it is important to note that the inclusion of legumes in crop rotation, although beneficial for nitrogen fixation, typically results in lower overall yields than cereals, adversely affecting total yield (Corbeels et al., 2020). This presents a challenge for implementing cereal and legume rotation in regions with food shortages. In addition, while rotation types with three species had the best effect in terms of relative CS yield, the introduction of a fourth crop resulted in decreased relative CS yield, requiring further investigation.

Weed and pest control is crucial in CS due to the favorable habitat it provides compared to CT (Pittelkow et al., 2015). Pests can significantly decrease crop yields, and even destroy entire crops, while weeds compete with crops for water, nutrients, and light heat resources, decreasing yields (Wang et al., 2023a). The use of herbicides and pesticides has shown promise in mitigating the adverse effects of CS on crop yield (Fig. 7a). Herbicides can effectively suppress weed competition during critical stages of crop growth, which may be challenging to achieve through manual or mechanical weeding alone (Nichols et al., 2015). However, it is important to consider the potential environmental and health impacts associated with herbicide and pesticide use to ensure the sustainability of the CS system. Alternative biological measures for weed and pest control, such as biocontrol agents, are being explored to address these concerns (Lyu et al., 2023).

Nitrogen fertilizer application in CS has shown mixed effects on relative yields compared to CT. Steward et al. (2018) found that low nitrogen application rates improved CS yields compared to CT and, even without nitrogen application, CS had positive relative yield performance. However, Rusinamhodzi et al. (2011) reported that CS required 100 kg ha^{-1} or more of nitrogen, with CS yields often higher than those of CT at higher nitrogen application rates. Our study highlighted that need for nitrogen fertilizer to maintain CS yields, as the absence of nitrogen application resulted in lower yields than CT (Fig. 7b), as reported by Rusinamhodzi et al. (2011).

Furthermore, the effectiveness of CS practices in increasing crop yield depends on crop type and no-tillage duration (Xiao et al., 2020). Our study found that CS produced significantly higher sunflower yields than CT, but lower maize yields. Therefore, the differential efficacy of CS practices across different crop types should be considered, with suitable regions and crop types selected to maximize CS benefits. According to our findings, no-tillage duration is an important factor affecting the impact of CS on relative yield (Fig. 3). Within a 10–20 year duration, CS increased crop yield compared to CT. However, shorter-term implementation (<5 years) often decreased crop yields because the beneficial improvements in soil properties and stabilization require time to develop during the transition from traditional tillage to CS (Cui et al., 2022). However, our research indicated that increasing the no-tillage duration does not guarantee continuous crop yield increases. When the no-tillage duration exceeded 20 years, crop yields significantly decreased (Fig. 5a). Prolonged no-tillage can lead to undesirable consequences such as increased soil bulk density, weed infestations, pest outbreaks, and diseases, all of which can have a detrimental impact on crop yield (Sun et al., 2024; Zhang et al., 2021). While the regression analysis showed a positive effect of no-tillage duration on relative CS yield (Fig. 5b), this could be due to the higher gains achieved by CS during the 10–20 year period (Fig. 5a). Recent research has shown that properly rotating no-till with conventional tillage can increase yields (Sun et al., 2023a, 2023b). Therefore, it is important to interpret research findings with caution, as the assumption that crop yield increases with no-tillage duration may not hold true in all cases.

4.4. Mechanisms of yield reduction in CS

Our analysis shows that crop yields are generally lower in CS than in CT in the short term. There may be several reasons for this phenomenon: firstly, CS generally increases soil bulk density and compactness compared to CT(Brouder and Gomez-Macpherson, 2014). This may be detrimental to the growth and development of crop roots, leading to a decrease in the ability of the roots to absorb soil nutrients and water, which ultimately reduces yield (Yu et al., 2023). Secondly, the main difficulty with CS is weed management. Cooper et al. (2016) conducted a meta-analysis of the effects of CS technology on weeds, yield and C storage. The results showed that CS increased weed incidence by more than 50 % compared to CT. CT can be used to control weeds (Peigné et al., 2018), while under CS, most weed seeds are exposed to the soil surface, where conditions are favorable for germination, so this can lead to high weed densities and thus increased competition for nutrients, water, light, and space from crop weeds (Mhlanga et al., 2022). Finally, CS may create unfavorable conditions for crop seed germination (Lamichhane et al., 2018). On the one hand, since CS promotes soil biodiversity, it can be assumed that in such systems there is an increased risk of seed predation by birds, ants and other pests; on the other hand, straw mulching reduces soil temperature and delays crop germination, especially in the presence of high soil moisture, where crop seeds are susceptible to pathogens and the risk of biotic stress may be higher.

4.5. Potential of CS to increase production

Our study suggests that the effectiveness of CS in improving crop yields is largely influenced by precipitation, temperature, soil properties, and crop types in the planting region (Fig. 3). Therefore, it is important to carefully assess the potential yield increase from implementing CS practices, considering the specific conditions of each region (Xiao et al., 2020). Adopting appropriate CS practices tailored to regional agricultural production and implementing sound management practices can minimize the adverse effects of CS on yield, and in some cases, even surpass the yield of CT (Table 2). For example, NT+M+R produced 18.79 %, 23.81 %, and 12.05 % higher relative yields in the north temperate, tropical, and south temperate zones, respectively, than NT-M-R. Notably, in hot and dry tropical areas, the increased effect of straw mulching on yield exceeded that of crop rotation (Table 2). However, it is important to note that the overall yield increases achieved through CS practices are relatively small (Fig. 6). For instance, in the dataset which predominantly represented the north temperate zone (87 %), optimal CS practices only increased yield by 0.78 % compared to CT (Table 2). This marginal increase in yield may not be significant for farmers who rely on grain yield and income as key indicators at the farm level (Corbeels et al., 2020). Thus, the potential for yield increases with CS in the north temperate zone appears limited. However, in the tropics, where food security is a critical concern in developing countries, the optimal combination of CS practices could increase yield by up to 5.43 %, offering valuable opportunities for sustainable agriculture and enhanced food production in these regions. Overall, CS yields are high in dry regions or in regions with soil pH > 7.5, and CS yields even exceed those of CT. The role of straw mulching and crop rotation should not be overlooked, especially in regions with < 400 mm of precipitation, where straw mulching should be emphasized. Of course, CS is also necessary in combination with appropriate N fertilization and weed and pest management.

4.6. Uncertainty analysis and prospects

As mentioned earlier, the impact of CS on crop yield depends on the combined effect of initial natural ecosystem type and farming practices (Xiao et al., 2020). However, a significant challenge is the lack of comprehensive and detailed data on natural conditions and management practices in field studies, with many studies not reporting essential variables such as fertilizer consumption, weed and pest control details, no-tillage duration, and other important factors such as temperature, seasonal precipitation, and soil type. Supplementing missing meteorological and soil data from external databases did not significantly affect the overall conclusions, it increased uncertainty (Su et al., 2021a; Wang et al., 2023b). Therefore, it is important to improve data recording and reporting of natural conditions and management measures in future field studies to help improve our understanding of CS and facilitate its regional promotion. Second, the random effects model was used for data analysis in this study, and although it can be effective in dealing with multilevel data or considering the correlation structure of the data, new analysis methods such as hierarchical correlation models may be more advantageous in dealing with clustered data or data with strong spatial correlation, and the use of hierarchical correlation models may be considered in the future for data analysis. Finally, although the funnel plot showed no publication bias, due to the large amount of data in the dataset, the heterogeneity of the dataset could be a source of publication bias. To ensure the accuracy and stability of the data, we also used the Egger's test, which showed $P>0.05$, further indicating that there was no publication bias in the dataset.

Furthermore, despite extensive research on CS, several aspects require further investigation, including the applicability of CS in different contexts, its ecological impact, and economic benefits. Given the long experimental period of tillage trials, future studies could use process-based models such as the denitrification and decomposition (DNDC) and root zone water quality models to simulate the entire growth cycle of crops under CS, including yield and specific greenhouse gas emissions.

It is important to acknowledge that real-world cropping systems are more complex and heterogeneous than experimental setups. While CS has demonstrated positive effects on sequestering soil organic carbon, reducing greenhouse gas emissions, achieving sustainable crop production, and increasing economic profits, especially in the context of climate change (Zhao et al., 2022), its adoption by farmers, especially in developing countries remains limited (Van Balen et al., 2023). This is due to several factors, including the short-term yield reduction under CS, which can discourage farmers from adopting these practices. In addition, some farmers lack the necessary equipment and knowledge to implement CS practices correctly, resulting in various challenges. Therefore, to promote CS effectively, it is essential to tailor its implementation to local conditions, while governments should increase awareness, provide necessary supports, and make economic investments to mitigate the risks of reduced yields and maximize the benefits of CS for farmers and the environment.

5. Conclusions

This study found that CS slightly reduced crop yield (1.35 %). However, the impact of CS varies depending on climate, soil and management conditions. Implementing region-specific CS practices can help minimize the risk of yield loss and optimize the benefits of CS. In arid regions or alkaline regions where soil pH is greater than 7.5, the use of CS can improve crop yields. Straw mulching is an important component of CS, especially under drought conditions, and greatly improves yields compared to no-till or rotational approaches. In addition, the no-till duration of CS has a significant impact on crop yields, with the highest yields occurring during the 10–20 year no-till duration, after which yields begin to decline. Therefore, the use of long-term no-till practices beyond 20 years may not be scientifically desirable, and a combination of conventional tillage and no-tillage rotations is expected to be more productive. Further analysis showed that CS has a greater potential for yield increases in the tropics than in temperate regions. However, yield is only one aspect of CS, and the practice has additional advantages in terms of maintaining soil health, conserving biodiversity and promoting environmental sustainability. Therefore, it is important to tailor CS practices to the specific natural conditions of each region and implement more science-based management practices to help balance soil health, food security and environmental sustainability in agricultural systems. Finally, due to the lack of CS duration and more detailed soil data such as soil bulk density, soil aggregate structure, soil organic carbon, microbial carbon and nitrogen, and microbial communities, this study did not provide a large-scale assessment of crop yield response to CS duration and the physical, chemical, and biological properties of soils, which deserves to be taken into account in future research.

CRediT authorship contribution statement

Jun Sun: Writing – original draft, Formal analysis, Data curation, Conceptualization. **Wenquan Niu:** Writing – review & editing, Funding acquisition. **Yadan Du:** Funding acquisition. **Li Ma:** Data curation. **Siying Huang:** Data curation. **Fei Mu:** Software, Data curation. **Qian Zhang:** Data curation. **Guochun Li:** Conceptualization. **Jinjin Zhu:** Data curation. **Kadambot H.M. Siddique:** Writing – review & editing.

Declaration of Competing Interest

We declare that this manuscript has not been published and is not under consideration for publication elsewhere. No conflict of interest exits in the submission of this manuscript.

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.still.2024.106265.

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