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Long-term effects of agronomic practices on winter wheat yield and NUE in dryland regions of USA and China: a long-term meta-analysis

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Dryland agriculture is fundamental to global crop production and vital to food security. Conservation tillage is extensively practiced in USA wheat cultivation. Meanwhile, the adoption of conservation tillage by Chinese farmers is limited. This meta-analysis compared the yield and nitrogen use efficiency (NUE) between conservation tillage and conventional tillage (CT) with different types of cropping systems, mulching methods, levels of nitrogen fertilizer (NF), and addition of manure. The meta-analysis presented that conservation tillage at high-NF enhanced the yield and NUE, and reduced the yield and NUE at low-NF, compared to CT. The interaction of conservation tillage with leguminous cover crops (LCC) and manure application increased the yield and NUE at low-NF, compared to CT. Non-leguminous cover crops (NLCC) increased the yield and NUE under high-NF than low-NF. The interaction of conservation tillage with management practices showed that the no-tillage (NT) with leguminous cover crops (LCC) significantly increased wheat yield by 58% and NUE by 47% under low-NF compared to CT. However, increasing the rate of NF did not increase the yield under such interaction. Cropping systems, mulching types, and manure application mainly determined the effects of conservation tillage on wheat yield and NUE. The adverse impact of CT on yield and NUE could be alleviated with the application of LCC and manure under moderate NF. We demonstrate that adding LCC and manure have a generally substitutive relationship with N fertilizer, resulting in a significant increase in wheat yield and NUE at low-NF doses as at high N fertilizer dosages. Therefore, based on the obtained results, moderate NF with LCC and manure application is recommended for growing winter wheat in dryland regions of the USA and China.

Keywords Long-term experiments, Crop management practices, Dryland winter wheat yield, Nitrogen use efficiency, Sustainable agriculture, Climate change

According to the IPCC Sixth Assessment Synthesis Report, the global average surface temperature of ocean and land increased by 1.1 °C from 2011 to 2020 compared to 1850 to 1900[1]. The temperature rise has harmed several natural systems and enhanced the frequency of extreme climate actions[2]. Due to its reliance on environmental conditions, climate change mainly affects agriculture. Decreased agricultural production may result from climate and weather circumstances such as flash floods, sporadic rain, hail and storms, frosts, and droughts[3]. The

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influence of extreme weather events like floods, droughts, wind storms, and modern climate change is primarily characterized by global warming and has altered the old condition of agricultural cultivation and significantly impacted crop productivity[4]. Dryland farming is vital to food security and a global agricultural system's key component[5–7].

Dryland farming areas cover more than 667 million ha, (> 70% of total farmland in China) with 267 million ha[8], while In the U.S., 40 percent of the land is considered dryland (U.S. Geological Survey, Department of the Interior, Dryland Ecosystems, 2016), this is the reason we choose to include the USA and China in this study. Farmers in dryland parts of the USA and Canada use the conventional tillage (CT) approach, which involves leaving the land bare after the harvest of the main crop until the plantation of the next crop to retain precipitation water and nutrients[9]. However, some studies suggested that in the dry land agriculture farming system, CT using a moldboard plough is ineffective in preserving soil moisture during a fallow period[10]. The soil becomes denser due to CT, forming a hardpan beneath the plough layer that obstructs water and airflow, stunting root growth and ultimately lowering crop production. Moreover, farmers continue to routinely prepare their fields for planting using rotary tillage and ploughing. Such conventional tillage worsens soil disturbance, has detrimental effects on the health of the soil, and is not a good choice for enhancing agricultural climate resilience[11]. Crop yields are typically constrained by nutrient deficits and seasonal water due to limited precipitation and fertilizers[12–14]. Because of this, agricultural yields remained low for an extended period and insufficiently supplied food to the local people[15,16].

It has been acknowledged that conservation tillage may be a helpful strategy for improving agricultural climate resilience. The Chinese Ministry of Agriculture and Rural Affairs promotes conservation tillage to lessen soil erosion and field dust, preserve soil fertility, and achieve harmony between nature and society[4]. Typically, there are three management principles of conservation tillage: (1) low or no soil ploughing (minimum or no tillage); (2) permanent covering of the soil provided by cover crops or retention of stubbles; and (3) rotation of the crops[17]. Increased soil water retention, reduced soil erosion, reduced fertilizer use, and labour savings are all benefits of conservation tillage[18].

The crop nutrient economy, mainly mineral nitrogen, requires substantial fossil energy inputs, a significant concern associated with tillage methods[19]. One of the key reasons limiting wheat productivity is a nutrient deficiency in the soil, particularly nitrogen deficiency[20], which could be improved by synchronizing fertilizer application with plant absorption requirements[21]. Conservation tillage methods affect the physical characteristics of the soil[22], impact nitrogen management[23], and temperature and moisture of the soil[24,25]. When the mixing of soil by cultivation practices is restricted because of plant rest humification, adopting conservation tillage methods can increase the temporary immobilization of nitrogen[26,27]. The soil fertility and productivity should be maintained using an adequate nitrogen management regime and an effective tillage system to increase the yield. Combining optimal fertilizer management and tillage methods[28] along with crop residue management can lessen the amount of nitrate leaching through fertilized fields[29]. According to previous research, more than 50% of the applied nitrogen is lost in intensive crop production systems through leaching or nitrous oxide emissions that cause environmental contamination[30,31];[32]. Data shows that the amount of mineral N fertilizers used in crops increased 7.4 times over 40 years. In contrast, the crop yield increased by just 2.4 times, supporting the ineffective and uneconomical use of nitrogen in crop production[33]. Therefore, the management approach to increase crop production and reduce the N losses into the environment and input costs of the farmers is to optimize nitrogen use efficiency (NUE, which is fertilizer N recovery efficiency) under diverse agroecological environments (climate, hydrothermal, chemical and physical properties of soil)[19,34].

A recent meta-analysis[35] has compared the different tillage methods with crop diversification and NF levels in Europe and Africa. However, they didn't include the mulching practices in their analysis. Mulching is used at a large scale to prohibit water evaporation and maintain soil temperature, which considerably affects crop yields. Moreover, the interaction of tillage with other agronomic practices in the USA and Chinese dryland agriculture under long-term experiments (LTEs) is still unclear. This study compiled the data from 30 LTEs with a minimum age of 10 years (except 2 articles having a period of 9 years; annexed in Table 1) in the USA and China to explore the relative yield effects of various agronomic practices and inputs to fill this knowledge gap. We hypothesized that (1) different agronomic practices such as conservation tillage, adding fertility crops, mulching, and manure at low-NF would improve wheat yield and NUE compared to respective control treatments. (2) Relative effects on yield and NUE may vary within tillage practices, cropping patterns, mulching methods, and the addition of manure.

Material and methods

Collection of data

Peer-review journal articles published between 1968 and 2023 were searched in Google Scholar (https://scholar.google.com/) and Web of Science (https://www.webofknowledge.com/) to evaluate the effects of different agronomic practices such as conservation tillage, multiple cropping, mulching, and addition of manure at different NF levels on wheat yield, and NUE. We used keywords for wheat yield, NUE, CT, conservation tillage, cropping pattern, manuring, mulching, and NF levels. Initially, we collected 625 publications and screened them by the following criteria:

- The studies should consist of at least ten years designated as long-term experiments (LTEs).
- The LTEs should be located in either China or USA and have at least one control treatment such as conventional tillage for conservation tillage evaluation, mono-cropping for cover cropping evaluation, which includes leguminous cover crops (LCC) and non-leguminous cover crops (NLCC), bare fallow for mulching comparison, 0 kg ha^{-1}-NF for different NF levels, and no manure application to manure application with similar edaphic and climatic conditions in the same experiment.

References	Country	Region	MAT (°C)	MAP (mm)	Soil texture	No of years	N rate (kg ha^{-1})	Tillage type	Crop management
[76]	China	Linfen	12	500	Medium	10	150	CT, NT, ST	SM
[77]	China	Shaanxi	12	500	Medium	10	150	CT, NT, ST	SM
[78]	USA	Mandan	5.5	422	Medium	12	0, 22, 45, 34, 67, 101	CT, NT	No mulching
[79]	China	Henan	13.9	615	Coarse	13	0, 75, 90, 150	CT	Manure
[80]	China	Shaanxi	10.7	555	Medium	13	0, 165	CT	Manure
[81]	China	Changwu	9.2	574	Medium	14	150	CT	PM
[82]	USA	Mandan	5.5	422	Medium	12	34, 67, 101	CT, NT	CC
[83]	USA	Mandan	5.5	422	Medium	12	34, 67, 101	CT, NT, RT	CC
[84]	USA	Idaho	5.6	685	Medium	13	112	CT, NT, RT	Stubble, CC
[85]	China	Linfen	10.7	355	Medium	22	150	CT, NT	Stubble
[86]	China	Pingliang	8	560	Medium	29	90	CT	Straw, CC, Manure
[87]	China	Heyang	10.5	526	Medium	12	150	CT, NT	No mulching
[88]	China	Changwu	9.2	574	Medium	13	N/A	CT, RT	SM, PM, Stubble
[89]	USA	Sidney	8.2	343	Medium	26	0, 45	NT, ST	Stubble
[90]	USA	Akron	7.3	418	Medium	24	11	CT, NT, RT	No mulching
[91]	USA	Akron	7.3	418	Medium	9	34	CT, NT	CC
[92]	USA	Kansas	13	429	Medium	14	0,10, 20, 30	CT, NT, RT	No mulching
[93]	USA	Oregon	11.3	320	Fine	23	45,90,135, 180	CT, RT	Stubble
[94]	USA	Oklahoma	16.3	814	Medium	20	0, 45, 90,134	CT	No mulching
[95]	USA	Kansas	12.4	429	Medium	25	11	CT, NT, RT	No mulching
[96]	USA	Kansas	12.4	429	Medium	17	67	CT, NT	CC
[97]	China	Beijing	13	529	Fine	9	0, 130, 300	CT	No mulching
[98]	USA	Akron	10.8	418	Medium	12	56	CT, NT, RT	No mulching
[99]	USA	Nebraska	10.7	685	Medium	24	45	CT, ST	CC
[100]	China	Heyang	10.5	582	Medium	10	75, 150,255	NT, RT, ST	No mulching
[101]	China	Multiple locations	9.7.4–14.6	450–570	Course	18	150	CT, NT, ST	SM, Stubble
[102]	China	Ganjing	11.5	526	Medium	10	150	CT, NT, ST	Stubble
[103]	China	Ganjing	11.5	526	Medium	10	75, 150, 255	CT, NT, ST	SM
[104]	China	Quzhou	10	180	Coarse	12	0, 50, 130, 150, 165	CT	No mulching
[85]	China	Shanxi	10.7	555	Medium	22	150	CT, NT	No mulching

Table 1. Information related to the studies on dryland winter wheat included in the meta-analysis.

Table 1 provides more information on each LTE, such as the type of cropping systems, treatment types, the number of replications, and the duration of experimental years.

Data analysis

We calculated standard deviations (SDs) as 10% of the mean for data without SDs. We manually collected the SD value for the studies without SD value by using the standard error (SE) by the formula below:

$$\mathrm{SD} = \mathrm{SE} \ \times \sqrt{\mathrm{n}} \tag{1}$$

where “n” denotes the sample numbers.

We also collected data on the experiments’ geographical location, experiment duration, and publication years. These experimental details help better interpret results in diverse climatic and management contexts.

The impact of conservation tillage (COT) associated to conventional tillage (CT) was calculated by using response ratio (RR). The natural log of RR was taken as effect size[36]:

$$RR = In\left(\frac{X_{cot}}{X_{ct}}\right) = In\left(X_{cot}\right) In\left(X_{ct}\right) \tag{2}$$

Xcot and Xct denote arithmetic mean fluxes of wheat yield and NUE under conservation tillage (COT) and conventional tillage (CT), respectively. The experimental design varied in observed studies. Wheat yield and NUE were observed separately within each study. Response ratios (RRs) were determined for every treatment, such as NT, RT, and ST with the CT (controlled). Error variance (V) was determined as follows[37].

$$V = \frac{S_{cot}^2}{N_{cot}X_{cot}^2} + \frac{S_{ct}^2}{N_{ct}X_{ct}^2} \tag{3}$$

where S_{cot} and S_{ct} are SD values, N_{cot} and N_{ct} designate the number of replications, and X_{cot} and X_{ct} are the mean for conservation and conventional tillage treatments, respectively.

The reciprocal of the variance (V) considered as the weight (W) for each RR was calculated by the following formula[36]:

$$W = 1/V \tag{4}$$

According to a process described by[37], individual RR values of conservation tillage and conventional tillage methods were used to compute the mean response ratio (RRE++), which was calculated as follows:

$$RR_{E++} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{m} W_{ij} RR_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{m} W_{ij}} \tag{5}$$

The letters "n" and "m" denote the treatment and comparison numbers within each category, respectively. The RRE++'s standard error was determined using the formula:

$$SE\left(RR_{E++}\right) = \sqrt{\frac{1}{\sum_{i=1}^{n}\sum_{j=1}^{m} W_{ij}}} \tag{6}$$

The comparison between no mulching (bare fallow) and mulched fallow, multiple cropping to mono-cropping, and no manuring to manuring with different NF levels were determined separately for every experiment.

We analyzed the data with MetaWin 2.1 (a random model, Sinaure Associate Inc., Sunderland, USA) to determine the effect of mulching with no mulching, multiple cropping to mono-cropping, and no manuring to manuring with three NF levels (0 NF, ≤ 100 kg N ha^{-1}, and > 100 N kg ha^{-1}) on yield, and NUE. In the analysis, 95% bootstrapped confidence intervals are produced along with the mean effect size. If the 95% confidence interval (CI) does not cross the zero (null) line, the effect of the conservation tillage systems is considered significant. Effect size (RR) was analyzed with Origin 2018 (OriginLab Corporation, USA) working on the principle of a single observation.

Results

Effects of different tillage systems and NF on winter wheat yield

To compare the relative effects of different NF levels, we took 0-NF as a control treatment. We separately compared it to different levels of NF (low-NF and high-NF) under each tillage method (Fig. 1). Shifting from low to high-NF irrespective of the tillage methods increased the yield (Fig. 1). High-NF increased the yield by 14, 42, 27, and 16% with CT, NT, RT, and ST, respectively, compared to control. Low-NF also significantly impacted yield, but the impact was low compared to high-NF. Low NF increased the yield by 7, 29, 20, and 11% under CT, NT, RT, and ST, respectively, compared to control (Fig. 1).

To compare the relative effects of different tillage methods, we took CT as a control treatment and compared it to different conservation tillage methods. Shifting from CT to conservation tillage methods increased the yield irrespective of the levels of NF (Fig. 2). Compared to CT, NT increased the yield by 48 and 23%, RT by 42 and 13%, and ST by 35 and 12% under high and low-NF levels, respectively. The effect of conservation tillage methods on wheat yield was non-significant under 0-NF when compared to CT (Fig. 2).

Effects of different tillage systems and NF on NUE

By increasing the amount of fertilizer from low to high increased the NUE irrespective of the tillage treatments (Fig. 1). CT, NT, RT, and ST increased NUE by 12, 31, 15, and 21%, respectively, at high-NF, compared to control which is 0-NF. CT, NT, RT, and ST increased NUE by 8, 22, 10, and 16%, respectively, at low-NF compared to control (Fig. 1). Compared to CT, NT increased NUE by 12 and 44%, RT by 5 and 37%, and ST by 8 and 31% under low and high NF, respectively (Fig. 2).

Yield responses to management practices under different tillage methods

No tillage

Interaction of NT related to CT and different NF levels under mono-cropping had variable effects on yield. 0-NF and low-NF had non-significant effects on yield under mono-cropping. In contrast, high-NF increased yield by 19% under NT, compared to CT. Crop diversification such as shifting from mono-cropping to multiple cropping with the increase of NF increased wheat yield under NT, compared to CT (Fig. 3). Multiple cropping such as NLCC and LCC had variable effects at different NF levels under NT than CT such as 0-NF had a non-significant effect under NLCC but increased the yield by 29% under LCC. The NLCC increased the yield by 22 and 26%, while LCC increased the yield by 58 and 55% at low and high NF, respectively, under NT compared to CT (Fig. 3).

Applying mulching such as straw, stubble, and plastic also had variable effects under NT than CT at different levels of NF such as straw mulching increased the yield by 8% but stubble and plastic mulching had a non-significant effect at 0-NF under NT compared to CT. Straw mulching increased the yield by 41 and 37%, stubble mulching by 33 and 18%, and plastic mulching by 36 and 31% at low and high-NF, respectively, under NT than CT. Application of manure under NT increased the yield by 19, 43, and 32% at 0, low and high-NF, compared to CT.

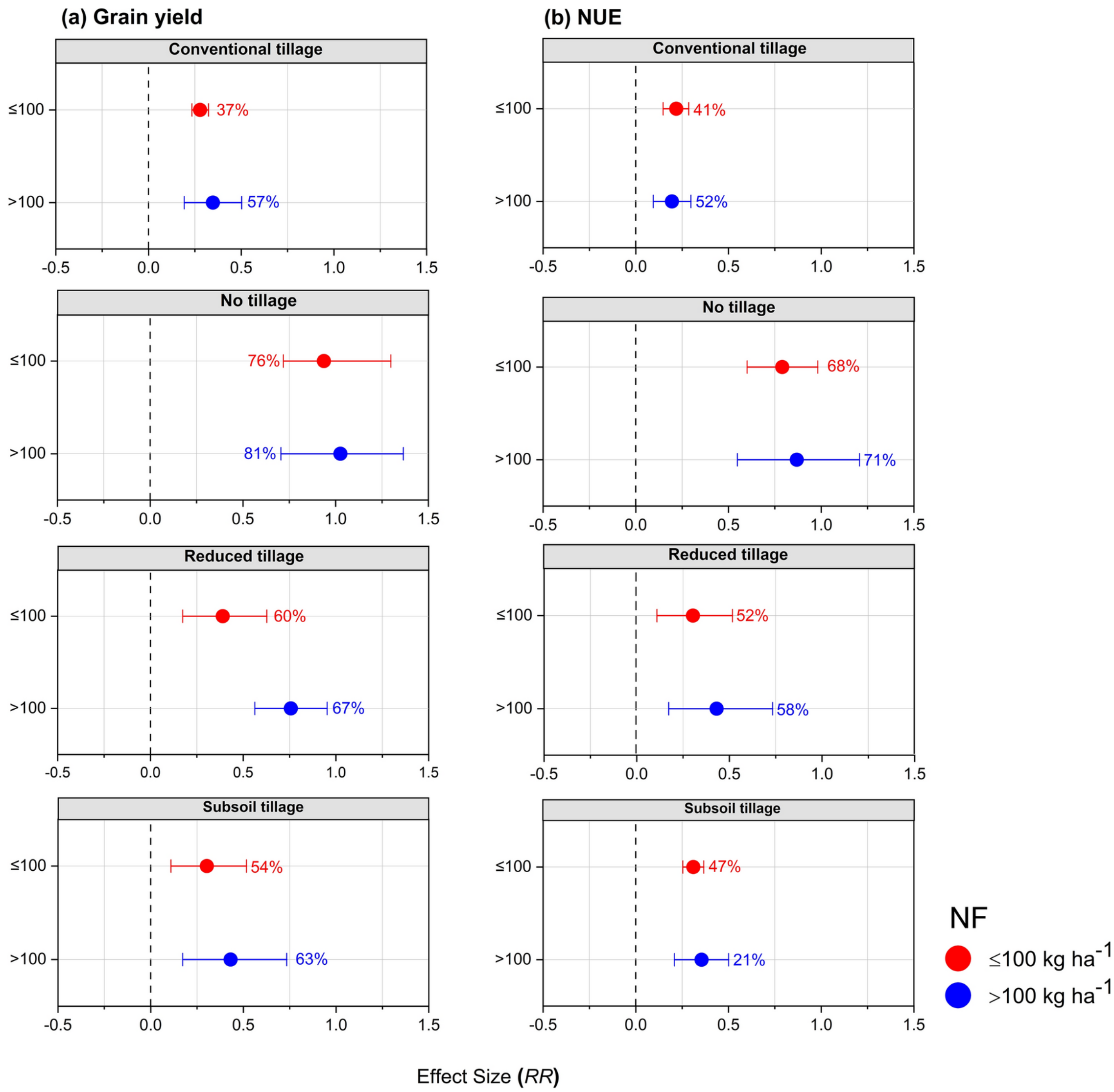

Fig. 1. The mean response ratios (RR) of winter wheat yield (**a**), nitrogen use efficiency (NUE, **b**) to nitrogen fertilization (NF) at ≤ 100 kg ha^{-1} and > 100 kg ha^{-1} compared to no NF, under different tillage methods. The horizontal line represents the bootstrapped 95% confidence interval. The reference line (RR = 0) specifies no variation between different levels of NF and no NF. Numbers accompanying the bootstrapped 95% confidence intervals designate percent increase in yield and NUE under different levels of NF as compared to no NF.

Reduced tillage

Mono-cropping had non-significant effects on yield under RT than CT at all NF levels showing the incompetency of RT in increasing the yield than CT in mono-cropping systems. Shifting from mono-cropping to multiple cropping with the increase in NF increased wheat yield under RT, compared to CT (Fig. 4). Applying multiple cropping such as NLCC and LCC had variable effects under RT than CT under different NF levels. For example, 0-NF had a non-significant effect under NLCC but increased the yield by 6% under LCC. Compared to CT, RT with NLCC increased the yield by 16 and 19%, and LCC by 32 and 18% at low and high-NF, respectively (Fig. 4). Applying mulching under RT at 0-NF had a non-significant effect on yield. While, straw mulching increased the yield by 35 and 27%, stubble mulching by 25 and 20%, and plastic mulching by 15 and 9% at low and high-NF, respectively, under RT than CT. Application of manure under RT increased the yield by 6, 37 and 19% with 0, low and high NF, respectively, compared to CT (Fig. 4).

Subsoil tillage

ST had variable effects on wheat yield under different management practices. Mono-cropping had a non-significant effect on yield under ST than CT at all NF levels. Shifting from mono-cropping to multiple cropping increased wheat yield under ST, compared to CT (Fig. 5). NLCC and LCC at 0-NF had non-significant effect under ST than CT. The yield was high at high-NF than low-NF under ST. ST with NLCC increased the yield by 11 and 16%, and with LCC by 22 and 19% with low and high NF, respectively, compared to CT. Applying

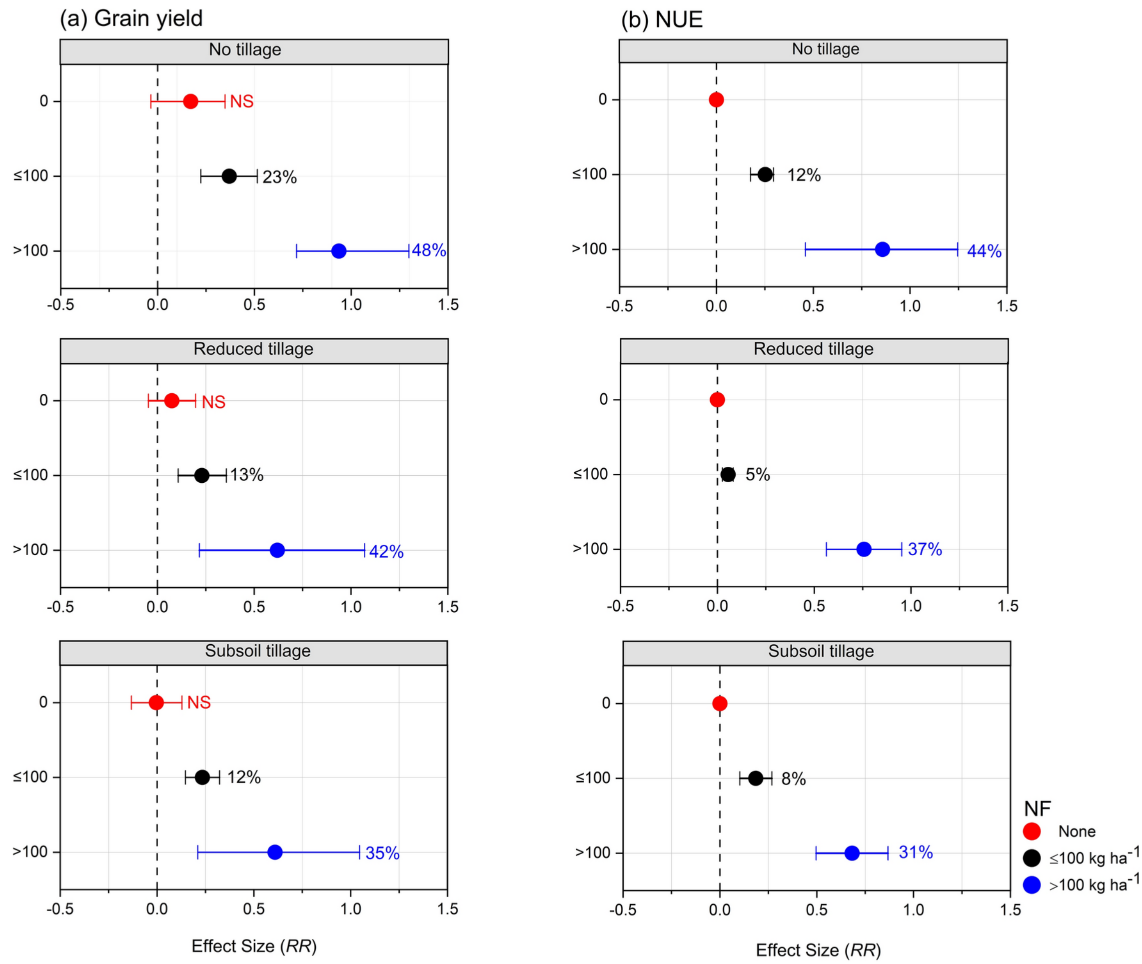

Fig. 2. The mean response ratios (RR) of winter wheat yield (**a**), nitrogen use efficiency (NUE, **b**) to nitrogen fertilization (NF) at 0 kg ha^{-1}, ≤ 100 kg ha^{-1}, and > 100 kg ha^{-1} under conservation tillage methods compared to conventional tillage. The horizontal line represents the bootstrapped 95% confidence interval. The reference line (RR = 0) specifies no variation between conservation tillage methods compared to conventional tillage. Numbers accompanying the bootstrapped 95% confidence intervals designate a percent increase in yield and NUE under different types of conservation tillage methods compared to conventional tillage.

mulching under ST at 0-NF had a non-significant effect on yield. Straw mulching increased the yield by 21 and 7%, stubble mulching by 19 and 9%, and plastic mulching by 20 and 17%, respectively, with low and high NF, under ST than CT. Application of manure under ST increased the yield by 8, 28 and 15% at 0, low, and high-NF, respectively, compared to CT (Fig. 5).

NUE responses to management practices under conservation tillage methods

No-tillage

Mono-cropping had variable effects on NUE under NT than CT. Low-NF had a non-significant effect on NUE, however, high-NF increased NUE by 10% under NT than CT in the mono-cropping system. Crop diversification such as the addition of NLCC and LCC (multiple cropping) had variable effects on NUE under NT than CT, such as NT with NLCC increased the NUE by 7 and 27%, while LCC by 47 and 8% with low and high NF, respectively, compared to CT. NT with straw mulching increased NUE by 31 and 9%, stubble mulching by 19 and 16%, and plastic mulching by 29 and 18%, respectively, with low and high NF, compared to CT. Application of manure accompanied with NT increased the NUE by 39 and 5% at low and high NF, respectively, compared to CT (Fig. 6).

Reduced tillage

Reducing the amount of fertilizer had a non-significant impact on NUE under RT in mono-cropping, while high-NF increased the NUE by 9%. Shifting from a mono-cropping to multiple cropping increased NUE under RT, compared to CT (Fig. 7). Compared to CT, RT with NLCC increased NUE by 13 and 6%, and with LCC by 21 and 11% at low and high NF, respectively. RT with straw mulching increased the NUE by 19 and 10%, stubble mulching by 13 and 7%, and plastic mulching by 14 and 10%, respectively, at low and high-NF than

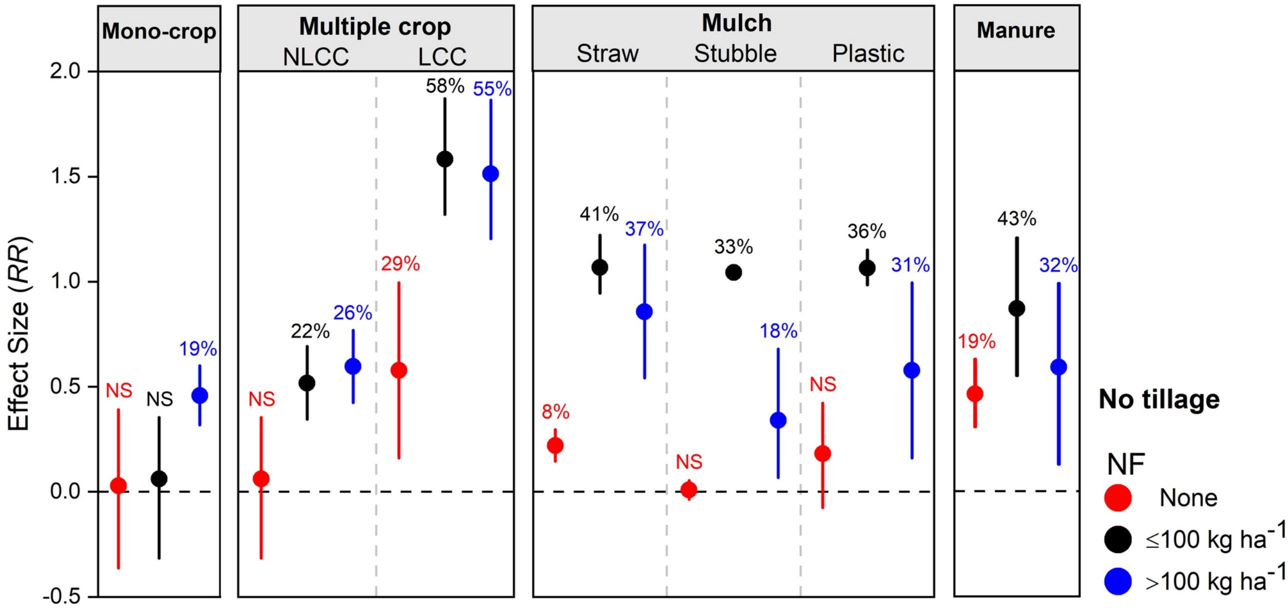

Fig. 3. The mean response ratios (RR) of winter wheat yield to nitrogen fertilization (NF) at 0 kg ha^{-1}, ≤ 100 kg ha^{-1} and > 100 kg ha^{-1} under no tillage compared to conventional tillage with mono-cropping, multiple cropping (non-leguminous cover crop and leguminous cover crop), mulching (straw, stubble and plastic), and manure. The vertical line represents the bootstrapped 95% confidence interval. The reference line (RR = 0) specifies no variation between no tillage compared to conventional tillage. Numbers accompanying the bootstrapped 95% confidence intervals designate a percent increase in yield under no tillage compared to conventional tillage.

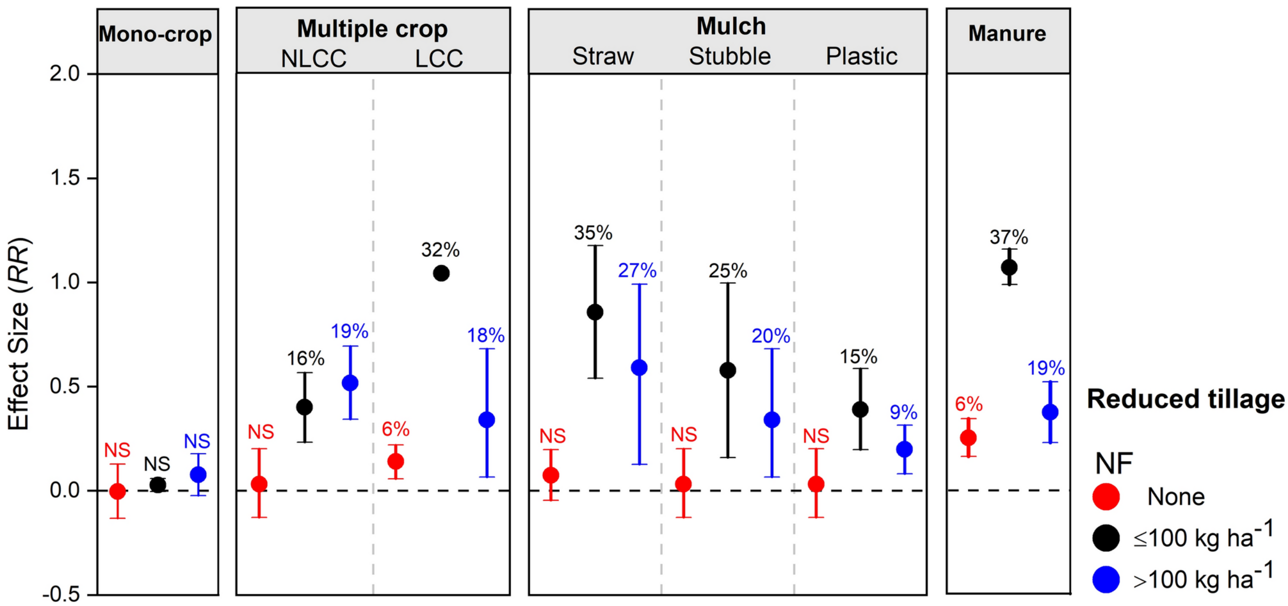

Fig. 4. The mean response ratios (RR) of winter wheat yield to nitrogen fertilization (NF) at 0 kg ha^{-1}, ≤ 100 kg ha^{-1}, and > 100 kg ha^{-1} under reduced tillage compared to conventional tillage with mono-cropping, multiple cropping (non-leguminous cover crop and leguminous cover crop), mulching (straw, stubble, and plastic), and manure. The vertical line represents the bootstrapped 95% confidence interval. The reference line (RR = 0) specifies no variation between reduced tillage compared to conventional tillage. Numbers accompanying the bootstrapped 95% confidence intervals designate a percent increase in yield under reduced tillage compared to conventional tillage.

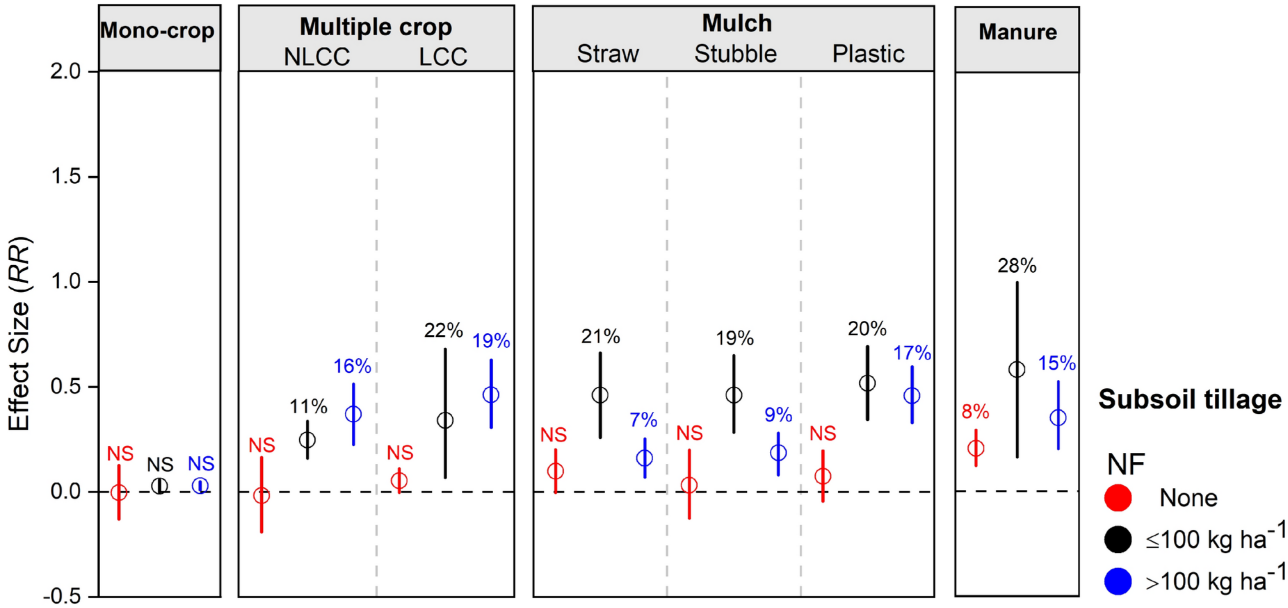

Fig. 5. The mean response ratios (RR) of winter wheat yield to nitrogen fertilization (NF) at 0 kg ha^{-1}, ≤ 100 kg ha^{-1} and > 100 kg ha^{-1} under subsoil tillage compared to conventional tillage with mono-cropping, multiple cropping (non-leguminous cover crop and leguminous cover crop), mulching (straw, stubble and plastic), and manure. The vertical line represents the bootstrapped 95% confidence interval. The reference line (RR = 0) specifies no variation between subsoil tillage compared to conventional tillage. Numbers accompanying the bootstrapped 95% confidence intervals designate a percent increase in yield under subsoil tillage compared to conventional tillage.

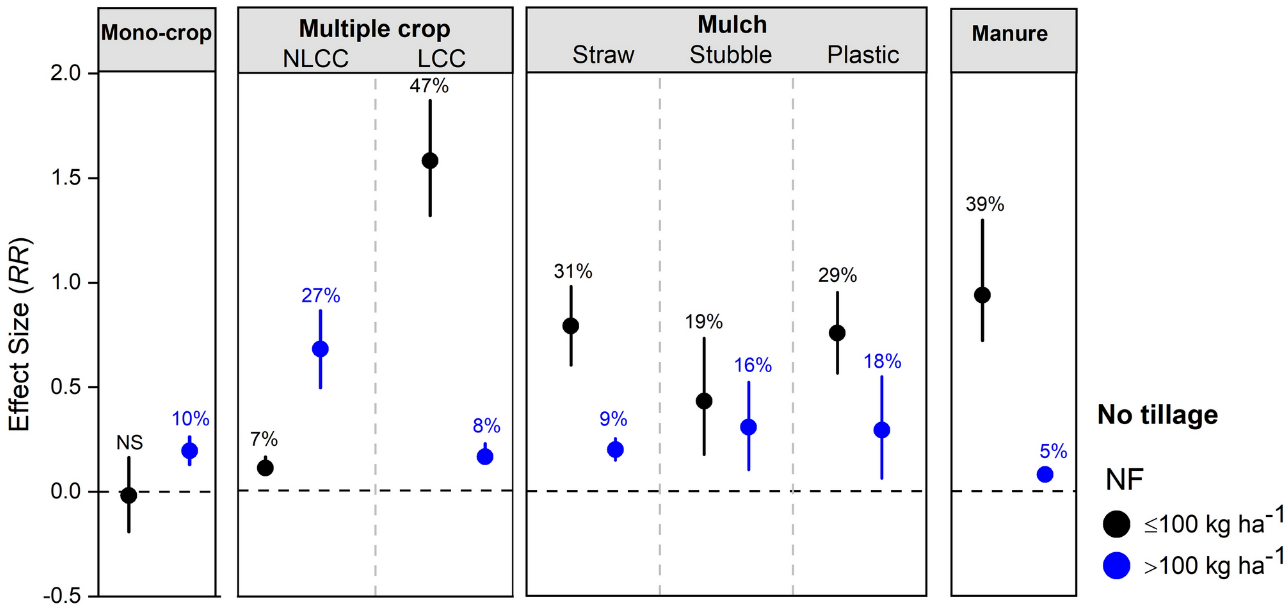

Fig. 6. The mean response ratios (RR) of nitrogen use efficiency to nitrogen fertilization (NF) at ≤ 100 kg ha^{-1} and > 100 kg ha^{-1} under no tillage compared to conventional tillage with mono-cropping, multiple cropping (non-leguminous cover crop and leguminous cover crop), mulching (straw, stubble and plastic), and manure. The vertical line represents the bootstrapped 95% confidence interval. The reference line (RR = 0) specifies no variation between no tillage compared to conventional tillage. Numbers accompanying the bootstrapped 95% confidence intervals designate a percent increase in yield under no tillage compared to conventional tillage.

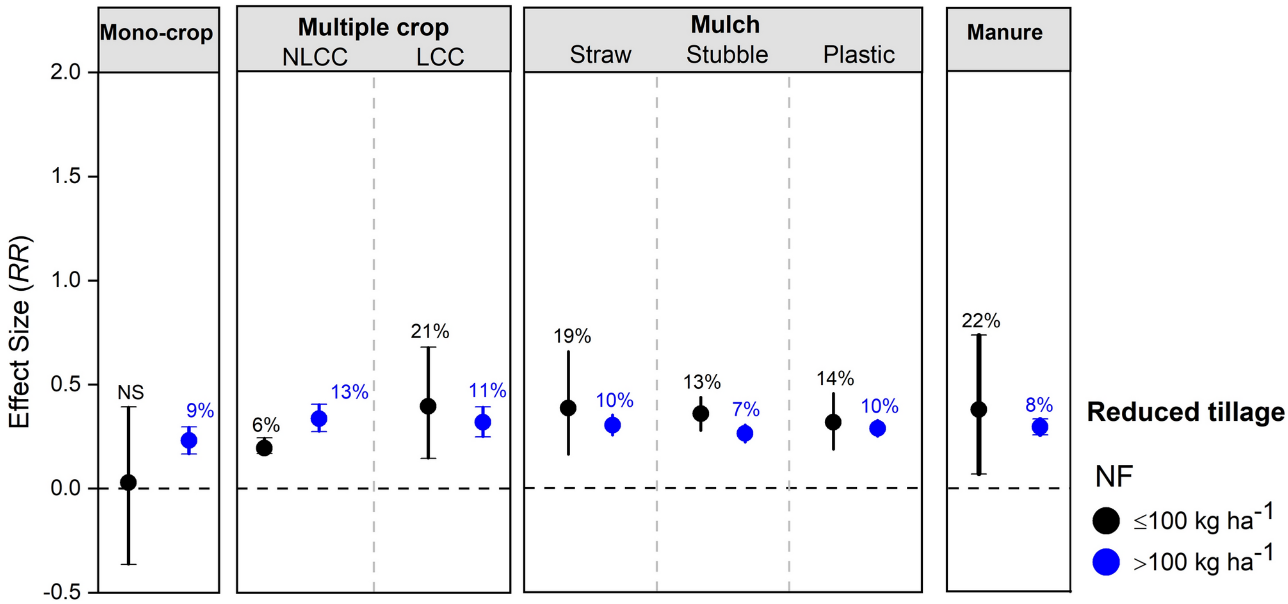

Fig. 7. The mean response ratios (RR) of nitrogen use efficiency to nitrogen fertilization (NF) at ≤ 100 kg ha^{-1} and > 100 kg ha^{-1} under reduced tillage compared to conventional tillage with mono-cropping, multiple cropping (non-leguminous cover crop, and leguminous cover crop), mulching (straw, stubble, and plastic), and manure. The vertical line represents the bootstrapped 95% confidence interval. The reference line (RR = 0) specifies no variation between reduced tillage compared to conventional tillage. Numbers accompanying the bootstrapped 95% confidence intervals designate a percent increase in yield under reduced tillage compared to conventional tillage.

CT. Compared to CT, manure application under RT increased the NUE by 22 and 8% with low and high-NF, respectively (Fig. 7).

Subsoil tillage
ST under mono-cropping had non-significant effect on NUE, compared to CT. Diversified cropping systems such as growing of multiple crops increased NUE under ST, compared to CT (Fig. 8). ST with NLCC increased the NUE by 10 and 7%, and with LCC by 23 and 9% with low and high-NF, respectively, compared to CT. Straw mulching increased the NUE by 21 and 12%, stubble mulching by 18 and 6%, and plastic mulching by 16 and 13%, respectively, with low and high-NF, compared to CT. Manure application under ST increased the NUE by 33 and 10% at low and high-NF, compared to CT (Fig. 8).

Generally, the conservation tillage at high-NF enhanced the yield and NUE and reduced the yield and NUE at low-NF, compared to CT. Among, conservation tillage methods, the highest increase in winter wheat grain yield and NUE were observed under NT, compared to RT and ST. Interestingly, the interaction of conservation tillage with LCC and manure application increased the yield and NUE at low-NF, compared to CT. However, NLCC increased the yield and NUE under high-NF than low-NF.

Correlation analysis between the effects of agronomic practices on winter wheat yield and climatic factors
Linear regression was used to analyze the effects of mean annual precipitation (Fig. 9) and mean annual temperature (Fig. 10) on wheat yield under different agronomic practices. The results showed that wheat yield was positively correlated with mean annual precipitation under the NT, RT, straw mulch and LCC treatments ($P < 0.05$) (Fig. 9). In terms of mean annual temperature, wheat yield was significantly positively correlated with mean annual temperature under the treatments of NT, straw mulch, plastic mulch and NLCC ($P < 0.05$) (Fig. 10). In contrast, the other management practices showed non-significant impacts on winter wheat yield (Fig. 10).

Discussion
Wheat yield
Cropping patterns
Shifting from mono-cropping to multiple cropping increased wheat yield under NT, compared to CT (Fig. 3). This confirms our hypothesis that diversifying from a monoculture and adding fertility crops will increase wheat yield (Figs. 3, 4, 5). Applying multiple cropping such as NLCC and LCC had variable effects under NT than CT, such as low-NF (0 kg ha^{-1} N), had non-significant effects under NLCC but increased the yield under LCC which corresponds to the findings of[35] who found that legumes interacted with NF to confine the effects of diversification.

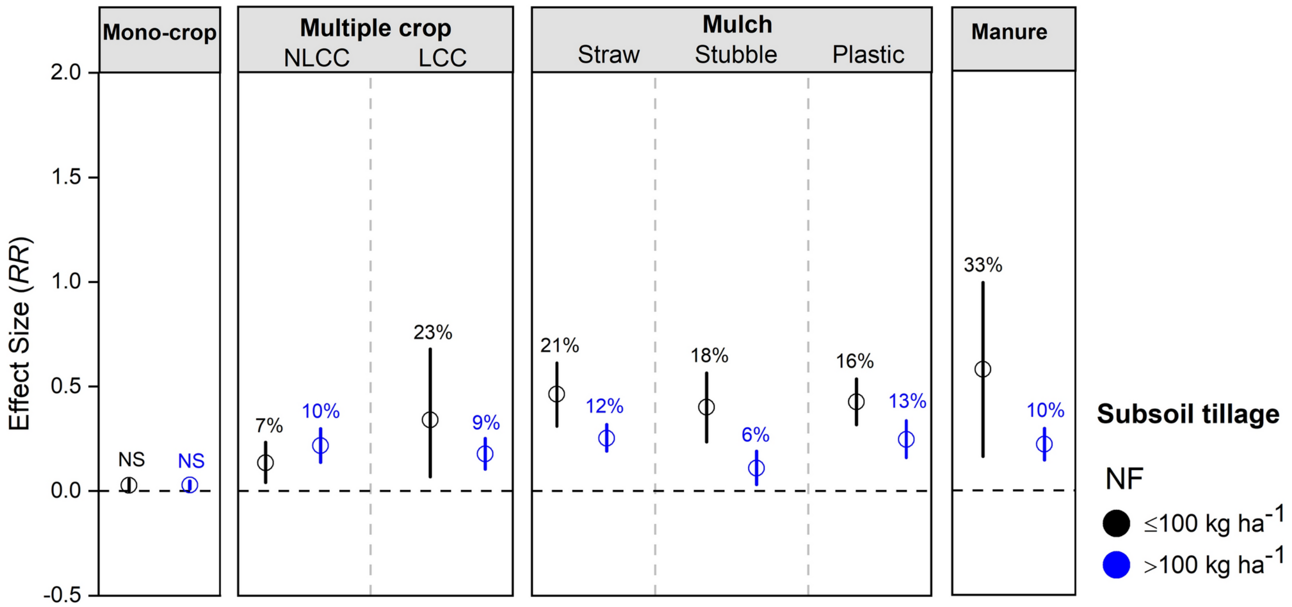

Fig. 8. The mean response ratios (RR) of nitrogen use efficiency to nitrogen fertilization (NF) at ≤ 100 kg ha^{-1} and > 100 kg ha^{-1} under subsoil tillage compared to conventional tillage with mono-cropping, multiple cropping (non-leguminous cover crop and leguminous cover crop), mulching (straw, stubble and plastic), and manure. The vertical line represents the bootstrapped 95% confidence interval. The reference line (RR = 0) specifies no variation between subsoil tillage compared to conventional tillage. Numbers accompanying the bootstrapped 95% confidence intervals designate a percent increase in yield under subsoil tillage compared to conventional tillage.

With the anthropogenic contributions examined in this study, we discovered that reduced NF under conservation tillage methods partially negatively affected yield under mono-cropping systems (Fig. 2) but had a strong positive impact under multiple cropping systems (Figs. 3, 4, 5). This shows that maintaining yields at or close to optimal levels while reducing tillage intensity may be a simple win to get some environmental advantages[38]. From the other angle, it also implies that raising tillage intensity does not significantly increase yields.

Compared to CT, diversification with legumes under conservation tillage methods (NT, RT and ST) exhibited more increase in yield when NF was low (≤ 100 kg ha^{-1} N) compared to high NF (> 100 kg ha^{-1} N). In comparison, the impact was antagonistic when wheat was diversified with non-legumes, resulting in a more significant yield rise under high-NF than under low-NF (Figs. 3, 4, 5). These results recommend that various types of cropping systems deliver diverse ecological functions under conservation tillage methods, such as when NF was low, legumes facilitated primary crop yields by biologically fixing nitrogen[39], while non-legumes likely contributed by regulation of weeds, pests, and crop diseases which turn out to be more significant at high NF[40]. Similar results were obtained by[41], who discovered that wheat production should employ less tillage and less (by 25%) nitrogen fertilization.

Mulching

Applying different types of mulching such as stubble and plastic mulching with 0-NF had non-significant effects under conservation tillage methods compared to CT. However, under conservation tillage methods at low and high NF, straw, stubble and plastic mulching significantly increased the yield (compared to no mulching), but the impact was more noticeable under NT straw mulching than other tillage and mulching methods (Figs. 3, 4, 5). The findings are similar to the previous research stating that compared to other mulching practices, straw mulching showed a better positive effect on wheat parameters, indicating that it may be a better option for the utilization of soil water in wheat crops[42,43]. Straw mulch, for example, has been found to improve soil quality by lowering water evaporation, cooling the topsoil, and increasing the amount of organic matter in the soil. Additionally, different mulching materials impact soils differently, such as water availability and grain yield increase when stubble residues are left on the ground.

The use of straw mulch is limited in the semi-arid regions of the Loess Plateau in northwestern China due to the possibility that it could lower the temperature of the soil surface, which will probably reduce grain yield. In contrast, plastic film mulching techniques successfully increase grain production in these locations to solve this issue[44]. According to one study on plastic mulching, a slight covering allowed more solar radiation to pass over the plastic film, heating the soil and air underneath it[15], whereas another study found that the "greenhouse effect" caused the topsoil to heat up more quickly during the day[45]. However, another study revealed that the water behind the layer decreased the longwave radiation, causing a cooling effect at night[15]. Additionally, it has been demonstrated that applying plastic film significantly lowers the heat flow and heat exchange between the air and

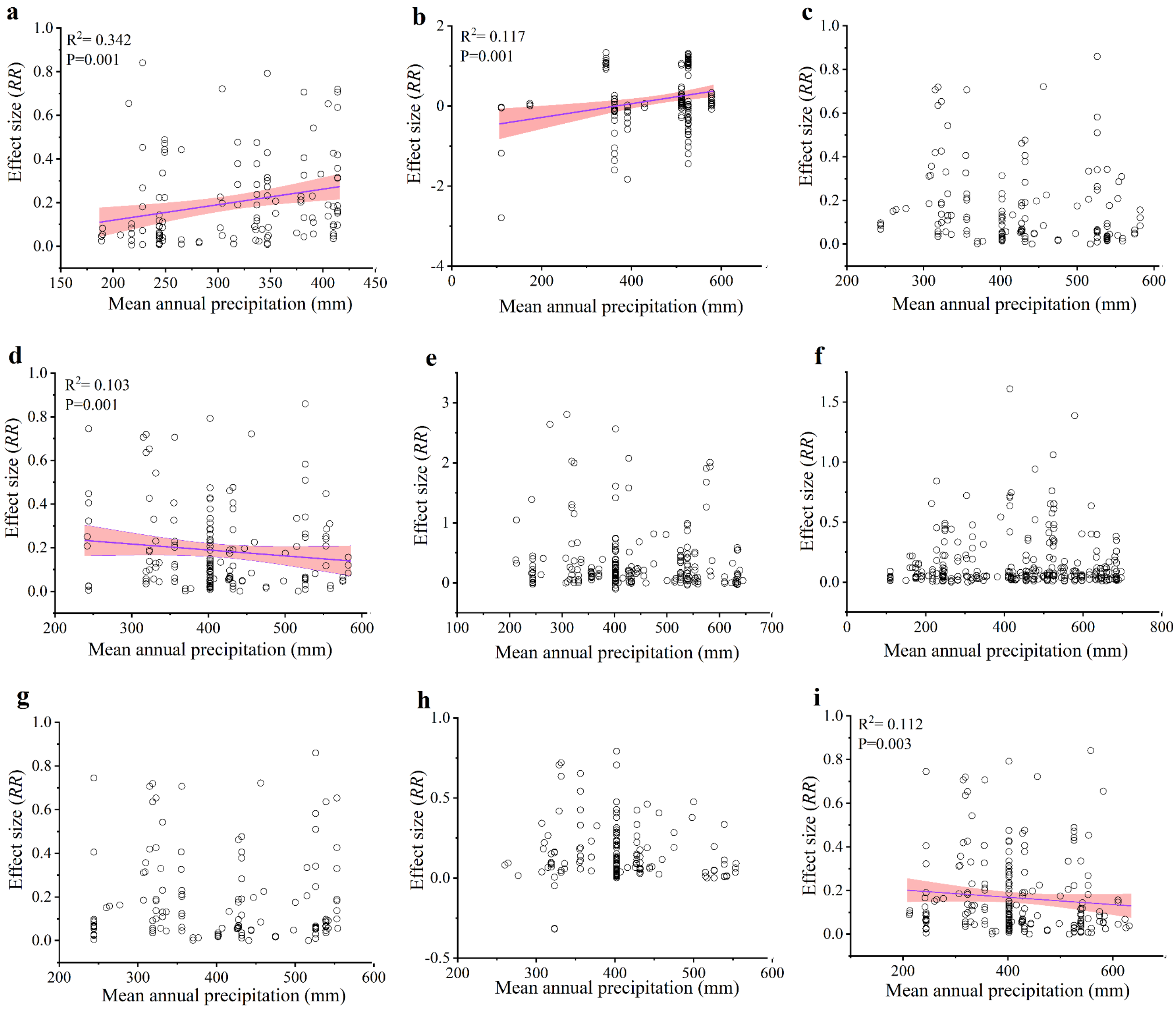

Fig. 9. Linear regression analysis of effect sizes of winter wheat yield and mean annual precipitation under different management practices. (**a**) No-tillage (**b**) Reduced tillage (**c**) Subsoil tillage (**d**) Straw mulch (**e**) Stubble mulch (**f**) Plastic mulch (**g**) Monocropping (**h**) Multiple cropping with non-leguminous crop (NLCC) (**i**) Multiple cropping with leguminous crop (LCC).

soil[46]. Gajri, et al.[47] discovered that the interaction of conservation tillage and mulching improved grain yield, while[48] illustrated how conservatively mulching and tillage could support plants more effectively in reaching nutrients and water from the subsoil. Hou, et al.[49] showed substantial changes in wheat production between conventional and conservation tillage systems, with crop yield increasing by 9.6 and 10.7% under NT and ST than CT, respectively. The possible reasons could be the improvement in physical and chemical properties of soil under NT[50], reduction in soil disturbance, improvement in aggregate stability and water holding capacity[51], that can be beneficial to save soil water when planting wheat, and acting as a barrier against brief droughts in cropping season that will ultimately rise crop yield[52,53]. Remarkably, conservation tillage reduces the amount of labor and energy needed to produce agricultural crops[54], and offer long-term advantages such as better soil structure, reduced soil erosion and farm disturbance[55].

Manure

Manure application increased wheat yield under all conservation tillage methods compared to CT (Figs. 3, 4, 5). However, the increasing impact was more under NT than other conservation tillage methods (Fig. 3). Additionally, the highest rise in yield was found under low-NF compared to high-NF. The findings correspond to a meta-analysis by[35], who stated that OM additions typically improved long-term crop yields, e.g., by increasing yields under low-NF and implying that the major impact of OM to crop yields was obtained from nutrient input. Additionally, applying OM at high-NF results in a slight increase in yield, possibly because of the release of other nutrients like potassium and phosphorus[40] or to improving soil structure and increasing soil carbon[56]. The highest impact in this regard is from manure applications, which allowed removing maximum N fertilizer from a

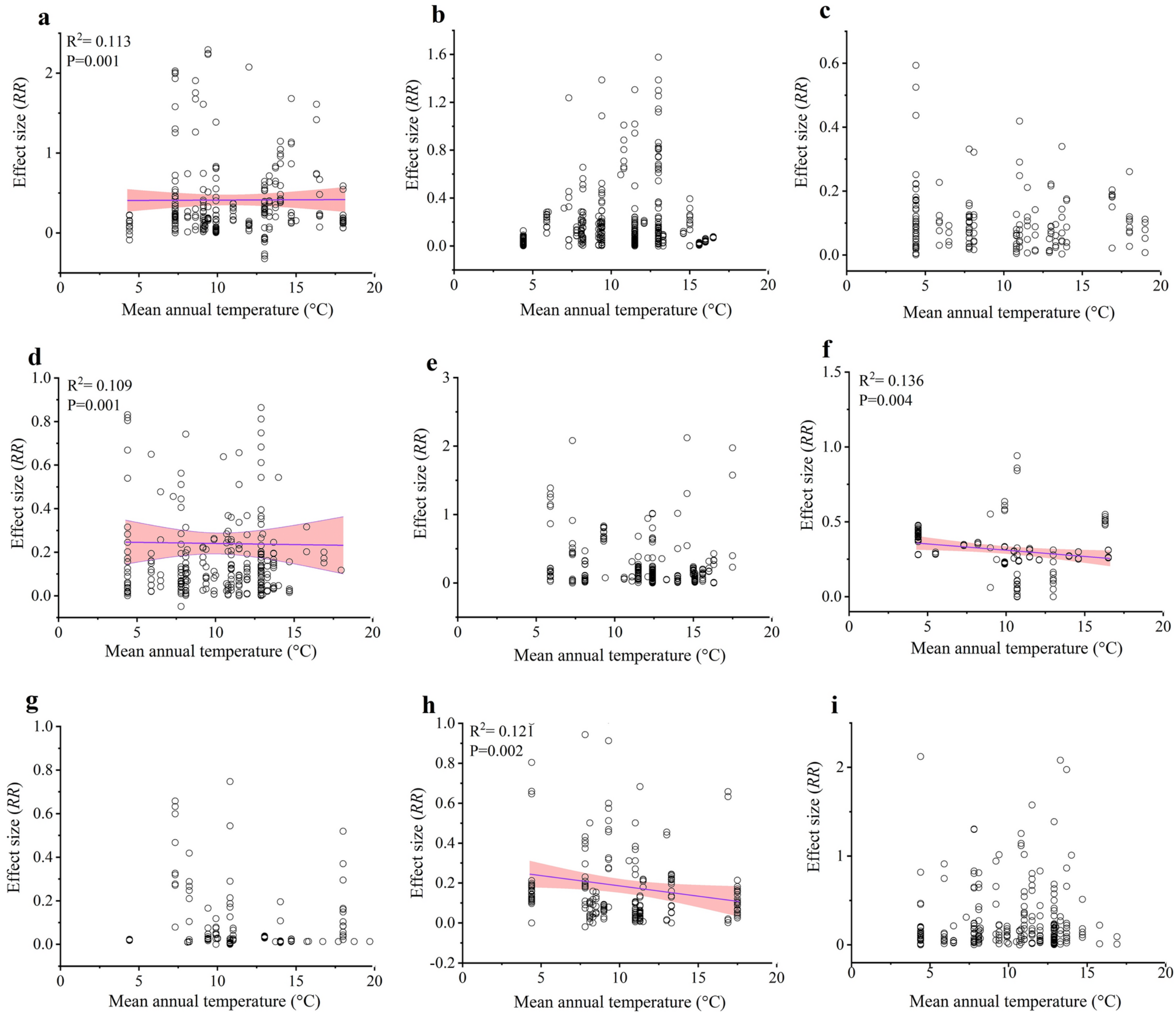

Fig. 10. Linear regression analysis of effect sizes of winter wheat yield and mean annual temperature under different management practices. (**a**) No-tillage (**b**) Reduced tillage (**c**) Subsoil tillage (**d**) Straw mulch (**e**) Stubble mulch (**f**) Plastic mulch (**g**) Monocropping (**h**) Multiple cropping with non-leguminous crop (NLCC) (**i**) Multiple cropping with leguminous crop (LCC).

system without a decrease in yield. The obtained results exhibit the competency of conservation tillage methods in mitigating the effects of N removal (Figs. 3, 4, 5).

Wheat nitrogen use efficiency

Nitrogen fertilizer

Generally, conservation tillage methods increased NUE at low NF compared to CT. (Fig. 2), corresponding to[57], who found that a moderate N application rate produced a high, stationary yield and a relatively high NUE of 240 kg ha^{-1}. This observation may be due to luxurious absorption by plants (excessive but inefficient absorption), and the application of N results in increased yield and N accumulation. If N application continues to rise and yield reaches saturation, the yield formation is absorbed inefficiently[58];[59]. This meta-analysis also showed this phenomenon in wheat production (Fig. 2). Crop roots frequently produce more sugars, sugar alcohols, and phenolics due to the higher nitrogen delivery rates, which alters the composition and richness of the soil microbes. As nitrogen application rates rise, denitrifying and ammonia-oxidizing bacterial activity also rises[60];[61].

Cropping patterns

Mono-cropping had variable effects on NUE under different tillage methods. However, the effect was more significant under NT among all tillage methods (Fig. 6). Mono-cropping with low-NF had a non-significant impact on NUE. In contrast, high-NF increased NUE under NT and RT, compared to CT (Figs. 6 and 7). These results agree with[62],[63], as they stated that the NUE was more under NT than CT in wheat crops. Diversifying from mono-cropping to multiple cropping increased NUE with low and high-NF irrespective of the tillage method applied (Figs. 6, 7, 8). Multiple cropping, such as NLCC and LCC had variable effects on NUE under different conservation tillage systems. The maximum NUE was obtained under LCC followed by NLCC at high-NF irrespective of the conservation tillage methods, compared to CT. The results correspond to the conclusions of[64], who observed that the NT, irrespective of the existence of cover crops, had a better positive effect on NUE for one of the two years in a two-year field experiment under the wheat cropping system. Following growth under NT cover cropping and NT, NUE traits were remarkably more than CT. Over two years, the field study revealed that switching to no-till improved crop NUE considerably compared to CT. Furthermore, both low and high N fertilization conditions exhibited this increase (Fig. 2).

Similarly[64], found that compared to conventional tillage, NUE was greater after no-till treatment (NT cover cropping and NT) and the NUE under these two NT conditions could be related to the improved health of the plants during vegetative growth[65], more promising environments for N uptake due to improved availability of soil moisture[66], and increased N mineralization that increased the accessibility of soil N[67].

Mulching

The conservation tillage methods (NT, RT and ST) at low and high NF, straw, stubble, and plastic mulching significantly increased the NUE. Still, the impact was more significant under straw mulching, irrespective of tillage methods (Figs. 6, 7, 8). High-yielding crops usually obtain extreme N fertilization to achieve higher yields because N is essential for plant growth[68]. Soil surface cover management in dryland agriculture directly impacts soil moisture loss, water storage and crop output[69]. According to[70] the use of plastic mulching can enhance the soil's hydrothermal conditions. In such conditions, inorganic nitrogen (N) in fertilizers is quickly converted to nitrate and diffuses to the crop roots, improving N absorption that encourages root growth and enlarging the effective N absorption area.

The findings of this meta-analysis are also similar to the results of[71] such as they had higher grain yields and enhanced NUE in soil treated with plastic mulching that could be due to the decreased direct soil water evaporation in the vertical direction by film mulching on the soil's surface[72]. Also, the increased N uptake during the mulching treatments may have decreased the soil's mineral N content, limiting N leaching.

Manure

The highest increase in NUE was observed under low-NF compared to high-NF under conservation tillage methods, compared to CT (Figs. 6, 7, 8), which could be due to the increased soil moisture and warmth that may enhance soil nitrogen availability and encourage crop N uptake, particularly in soil treated with manure (Zhao et al., 2014). Adopting NT is an important step in dryland farming to reduce the deterioration of soil physical and chemical properties and boost crop yield[69,73]. In this meta-anlysis, the results showed that among conservation tillage methods, manure application under NT showed the highest increase in wheat yield and NUE compared to RT and ST (Figs. 6, 7, 8), which could be due to the enhanced soil physical and chemical properties under NT. Several studies have demonstrated the positive effects of adding organic matter on soil characteristics[74]. observed significant improvement in soil physical–chemical properties under continuous application of manure. Moreover, high N fertilization is applied to achieve higher yields[68,75]. found that applying manure with N fertilizer was an effective way to conserve soil organic matter content under RT. However[75], found that the manure application with NF of 100 kg ha^{-1} under NT increased crop yield, as compared to the plots having no manure application, which corresponds to the results obtained by current meta-analysis.

Conclusion

This study compared the yield and nitrogen use efficiency (NUE) of wheat cultivation using conservation tillage and conventional tillage (CT) under different agronomic practices in the USA and China. The causes for the variances in the choice of tillage practices were also analyzed. The meta-analysis revealed that conservation tillage methods had higher yield and NUE at high-NF but lower yield and NUE at low-NF, compared to CT in mono-cropping systems. Cover cropping, particularly LCC, under conservation tillage methods increased yield and NUE at low-NF compared to CT. Replacing manure with NF can also increase wheat yield and NUE under conservation tillage methods. The adverse effects of CT on yield and NUE can be reduced by applying LCC under moderate NF. Cover cropping, mulching, and manure application are all effective at all tillage intensities, and conservation tillage significantly impacts yields and NUE. Our findings suggest that adding LCC and manure can partially replace N fertilizer under NT, significantly increasing wheat yield and NUE at both low and high N fertilizer levels.

Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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M.A, H.L, S.L, S.B and I.G perceived the review and draft and finalized the manuscript. FL, T.L, L.C, Z.W and W.F improved the draft and provided valuable suggestions. All authors contributed to the article and approved the submitted version.

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Declarations

Competing interests

The authors declare no competing financial interests.

Ethical approval

Not applicable.

Additional information

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