https://doi.org/10.17221/96/2025-AGRICECON

Effects of different tillage practices on cropland carbon efficiency in wheat–maize rotation cropping

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Citation: Wang Y., Wang B., Bai X. (2026): Effects of different tillage practices on cropland carbon efficiency under wheat–maize rotation cropping. Agric. Econ. – Czech, 72: 407–416.

Abstract: Enhancing cropland carbon efficiency (CCE) is vital for carbon-neutral and sustainable agricultural development. In this paper, we use the minimum distance to strong efficient frontier with undesirable outputs model and survey data from wheat–maize farmers in the Yellow River Basin of China in 2020 to investigate the effect and mechanism of different tillage practices on CCE. The results show that the average CCE in the study area is 0.592 6, which has large potential for improvement. Among the tillage practices, reduced tillage with straw returning (RTS) achieves the highest mean CCE, followed by no-tillage with straw returning (NTS), and conventional tillage with straw returning performs the worst. Both NTS and RTS are positively associated with higher CCE, with a stronger effect for NTS. Mechanism test results indicate that these practices enhance CCE primarily by increasing yield and net carbon sequestration. NTS improves CCE by reducing energy use and emissions, and RTS tends to increase fertiliser and energy inputs, partially offsetting its efficiency gains. Heterogeneity analysis results further indicate that the positive effects are stronger among small-to-medium-scale, less-educated and elderly farmers. These findings provide micro-level evidence that conservation tillage can promote low-carbon and efficient agricultural production in China.

Keywords: conservation tillage; greenhouse gas mitigation in agriculture; influence mechanism; MinDS-U model; sustainable agriculture

Greenhouse gases (GHG) emissions from agriculture and land use contribute approximately one-fifth of global emissions (Tubiello et al. 2021), making agriculture the second-largest source of emissions worldwide. Unlike other sectors, agriculture plays a dual role by both emitting carbon and sequestering it through soils and crop biomass (Cui et al. 2022). This duality creates substantial potential for mitigating emissions while enhancing carbon sinks, positioning agriculture as a key contributor to carbon peak and carbon neutrality goals.

In response to growing concerns about food security, cropland protection and low-carbon development, governments increasingly face the challenge of reconciling agricultural productivity with emission reduction and carbon sequestration objectives. Improving cropland carbon efficiency (CCE) is a key way to achieve this balance. CCE refers to the capacity of agricultural production systems to achieve high output while minimising carbon emissions, thereby reflecting both resource use efficiency and environmental performance (Su et al. 2023). Therefore, enhancing CCE has emerged as both a critical scientific issue and an important policy priority.

Existing studies of CCE differ substantially in their treatment of carbon outcomes, methodological approaches and analytical scale. Whereas early work relied on single-factor indicators, investigators in more recent

Funded by the National Social Science Foundation of China (24XJY036), the Special Project of Scientific and Technological Innovation of Xinjiang Research Institute of Arid Area Agriculture (XJHQNY-2025-8), Ministry of Education of Humanities and Social Science Foundation (22YJA790001), and the Science and Technology Project of Yulin (2024-CXY-187).

https://doi.org/10.17221/96/2025-AGRICECON

studies have adopted data envelopment analysis methods to incorporate carbon emissions and, in some cases, carbon sinks (Qiao et al. 2023; Elahi et al. 2024; Huang et al. 2024b). However, most existing research remains at macro levels or relies on emission intensity indicators, so investigators using such approaches overlook the offsetting role of soil and residue carbon sinks and therefore pay limited attention to soil carbon pools, farm-level behaviour and tillage practices. The main approaches, key points and limitations of the related literature are summarised in Table S1 (Electronic Supplementary Material – ESM). To overcome this limitation, we adopted CCE as a comprehensive metric that integrates expected output, carbon emissions and net carbon sequestration, thereby capturing carbon-constrained production efficiency at the farm level.

Tillage practices are widely recognised as a key determinant of CCE, as they influence both emission pathways through soil disturbance and input use and sequestration pathways through residue retention and soil organic carbon accumulation (Bhattacharyya et al. 2022). Although conservation tillage (CT) has been shown to reduce GHG emissions and enhance soil carbon stocks, most existing evidence is derived from experimental or plot-scale studies, offering limited insight into how farmers' actual tillage choices affect CCE within heterogeneous production conditions. This gap motivates the core research question of this study – namely, how different tillage practices affect farmers' CCE within a common production context.

Despite the theoretical relevance of tillage practices for CCE, in our review, we reveal three notable gaps in the literature. First, investigators in much of the existing literature considered only crop carbon sinks and ignored soil carbon pools. This omission yields incomplete and potentially biased estimates of CCE, which tend to lead to underestimation of actual efficiency levels. Second, the mechanisms linking farmers' tillage decisions to CCE have seldom been explored from a social science perspective. Most existing studies are grounded in field trials or technical experiments, with little attention given to behavioural and institutional factors, making their results less suitable for broader evaluations of CCE and potentially leading to biased policy implications. Third, much of the literature focusses on provinces or regions at the macro level. This perspective neglects micro-level heterogeneity in tillage adoption and results in an incomplete understanding of policy effectiveness, land sustainability and institutional development of green production.

Therefore, in this study, we address these gaps by incorporating both crop and soil carbon sinks into the efficiency measure, establishing an analytical framework that connects tillage practices to CCE through yield, soil carbon sequestration and input use, and by using household survey data from farmers in China. Specifically, we analyse in detail the CCE across conventional tillage with straw returning (CTS), no-tillage (NT) with straw returning (NTS) and reduced tillage (RT) with straw returning (RTS) within a common production context by using cross-sectional data from the farm level of wheat–maize rotation in 2020.

The study contributes to the literature in three ways. First, it provides micro-level evidence about the efficiency implications of CT on CCE in China, thereby supplementing findings from previous studies based on experimental plots or macro-level data. Second, we develop a more comprehensive CCE measurement method that incorporates carbon emissions and sequestration, with an emphasis on soil carbon, by using the improved minimum distance to strong efficient frontier (MinDS) model to obtain more accurate efficiency estimates. Third, we emphasise the role of farmer heterogeneity in influencing the effectiveness of tillage practices, offering insights that are directly relevant to policy design and farm-level decision-making.

Theoretical framework and hypotheses. Existing research has largely focussed on how tillage practices affect carbon emissions and sequestration in croplands but has left their implications for CCE insufficiently examined. Within conditions of limited arable land, conventional tillage often prioritises output maximisation through intensive input use and soil disturbance, which increases GHG emissions and undermines land use sustainability (Li et al. 2023). In contrast, CT practices, including NT, RT and straw returning, can minimise soil disturbance, maintain surface residues and sustain productivity with lower environmental costs (Han et al. 2025). On the basis of the carbon-constrained production theory, we focussed this section on discussing the mechanisms by which tillage practices affect CCE from three aspects: input-related carbon emissions, soil carbon sequestration and yield effects (Figure 1).

First, tillage practices affect CCE by altering input-related carbon emissions. Straw returning improves soil nutrient availability and can reduce reliance on chemical fertilisers, thereby lowering fertiliser input-induced carbon emissions (Song et al. 2024). NT and RT also reduce the frequency of mechanical operations, leading to lower energy use and associated carbon emissions, although RT may partially offset these gains

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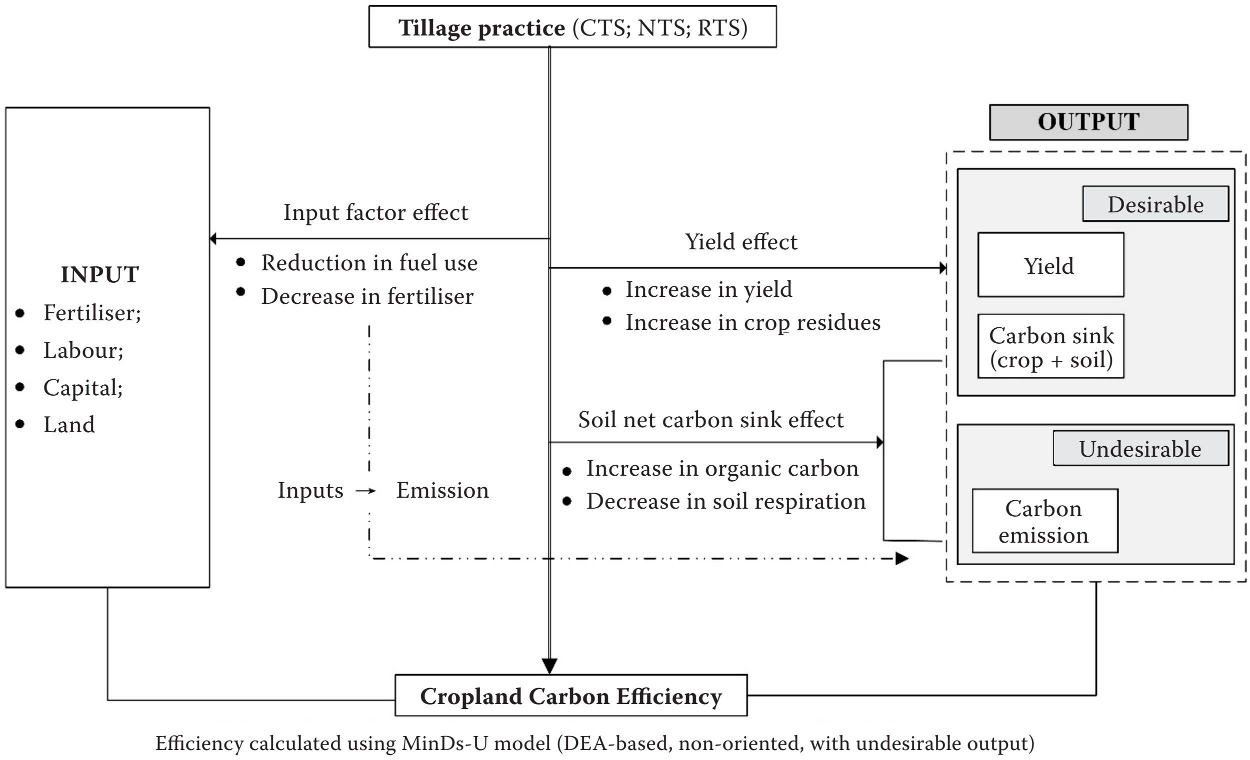

Figure 1. Mechanistic framework: Tillage practices and cropland carbon efficiency

CTS – farmers who adopted conventional tillage with straw returning; DEA – data envelopment analysis; MinDS-U – the minimum distance to strong efficient frontier with undesirable outputs model; NTS – farmers who adopted no-tillage with straw returning; RTS – farmers who adopted reduced tillage with straw returning
Source: Authors' own elaboration

through higher power requirements in deeper soil operations (Bhattacharyya et al. 2022; Cantero-Martínez et al. 2025). Second, tillage practices regulate the soil's net carbon sink capacity. By limiting mechanical disturbance and protecting soil aggregates, NT and RT preserve soil organic carbon and reduce microbial respiration, thereby enhancing carbon retention (Li et al. 2023). Straw returning further supports soil carbon accumulation by providing organic substrates, although the magnitude of sequestration effects may vary across soil layers and management contexts (Huang et al. 2024a). Third, tillage practices influence crop yields, which in turn affect CCE through productivity. CT systems can maintain or increase yields by improving soil structure and stability, but yield responses remain context dependent. In some cases, NT may constrain early crop growth owing to soil compaction or lower temperatures, leading to modest yield reductions (Beres et al. 2025).

Drawing on these ideas, the we proposed the following hypotheses:

H_1: CT practices are more positively associated with CCE than is conventional tillage.

H_2: The effect of tillage practices on CCE operates through three channels: yield enhancement, reduction in input-related carbon emissions and increased soil carbon sequestration.

MATERIAL AND METHODS

Data source

We collected the data through a field survey conducted in Shaanxi, Shanxi and Henan provinces, which represent the core wheat–maize rotation region of the Yellow River Basin in China. The production information corresponds to the complete 2020 rotation cycle. We used a multistage random sampling strategy at the county, village and household levels. After we excluded observations with incomplete or inconsistent information, the final sample included 633 farm households with complete production data for the 2020 rotation. Given the widespread adoption of mechanised harvesting and straw use in the study area, wheat straw is assumed to be fully returned to the field for all sampled households. This assumption simplifies the calculation

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of carbon emissions and sequestration and reflects prevailing production practices in the region.

Key variables

Core independent variables. We adopted a quasi-experimental design in which households practicing CTS served as the control group. In contrast, we treated households adopting NTS and RTS as the experimental groups. Tillage practices are the core explanatory variables and are represented by binary indicators for NTS and RTS.

Dependent variable. The dependent variable was *CCE*, which integrates economic performance with carbon emission reduction and carbon sequestration in a single metric. Compared with traditional indicators such as land productivity or carbon emission intensity, *CCE* provides a more integrated framework for evaluating low-carbon agricultural development. We used the common slacks-based measure model to evaluate inefficiency relative to the farthest frontier point, which may lead to overestimating adjustment needs and underestimating efficiency. In contrast, the MinDS model projects units onto the nearest point on the strong efficient frontier, yielding a more realistic efficiency measure (Aparicio et al. 2007). Thus, in this study, we used the Minimum Distance to the Strong Efficient Frontier model with undesirable outputs (MinDS-U). The Decision-Making Units (DMUs) are individual farm households engaged in wheat–maize rotation. *CCE* was obtained by solving the following problem:

$$maxCCE_k = \frac{1-\frac{1}{I}\sum_{i=1}^{I}\frac{s_i^{x-}}{x_{ik}}}{1+\frac{1}{P+Q}\left(\sum_{p=1}^{P}\frac{s_p^{y+}}{y_{pk}}+\sum_{q=1}^{Q}\frac{s_k^{b-}}{b_{qk}}\right)} \quad (1)$$

$$s.t.\sum_{j\in E}\lambda_j x_{ij} + s_i^{x-} = x_{ik}, i = 1,2,\ldots,I \quad (2)$$

$$\sum_{j\in E}\lambda_j y_{pj} - s_p^{y+} = y_{pk}, p = 1,2,\ldots,P \quad (3)$$

$$\sum_{j\in E}\lambda_j b_{qj} - s_q^{b-} = b_{qk}, q = 1,2,\ldots,Q \quad (4)$$

$$-\sum_{i=1}^{I}V_i x_{ij} + \sum_{p=1}^{P}U_p y_{pj} - \sum_{q=1}^{Q}W_q b_{qj} + d_j = 0, j \in E \quad (5)$$

$$s_i^{x-}, s_p^{y+}, s_q^{b-} \geq 0 \quad (6)$$

$$V_i, U_p, W_q \geq 1 \quad (7)$$

$$0 \leq \lambda_j \leq M\left(1-r_j\right), j \in E \quad (8)$$

$$0 \leq d_j \leq M \times r_j, j \in E \quad (9)$$

$$r_j \in \{0,1\}, j \in E \quad (10)$$

where: CCE_k – the efficiency value of the k^{th} DMU; x_{ik} – the i^{th} input of k^{th} unit; y_{pk} and b_{qk} – the p^{th} desired output and the q^{th} undesired output; s_i^{x-}, s_p^{y+} and s_q^{b-} – the slack variables of the above three types of vectors, respectively; λ_j – the combination coefficient; M – a sufficiently large positive integer.

Constraints [Equation (5–10)] restrict the reference benchmarks to the same hyperplane. Each DMU is characterised by a set of inputs, desirable outputs, and undesirable outputs (details in Table 1). The estimate details of carbon emissions and sinks are presented in the Text S1 and Text S2 in the ESM.

Control variables. To minimise the potential effect of confounding factors on CCE, we selected household head characteristics, land characteristics, farm household characteristics and regional variables as control variables. Specifically, household head characteristics included the household head's gender, age and education; in terms of land characteristics, we selected cultivated land area, irrigation conditions and land fragmentation; household characteristics are represented by agricultural income and nonagricultural employment. The definition and descriptive statistics of variables are shown in Table S2 (ESM).

Econometric model

We used the Tobit model to estimate the effects of tillage practices on CCE, accounting for its truncated distribution. The Tobit model is specified as Equation (11):

$$CCE_i = \alpha_1 + \beta_1 tillage_i + \gamma control_i + \varepsilon_i \quad (11)$$

where: CCE_i – the i^{th} farmer's CCE; $tillage_i$ – the tillage practice decision of i^{th} farmer; $control_i$ – a vector of control variables; α_1 – the intercept; β_1 and γ – coefficients to be estimated; ε_i – the error term.

To further clarify the transmission mechanism through which tillage practices affect CCE, we established the following model to test the underlying mechanism:

$$M_i = \alpha_2 + \beta_2 tillage_i + \gamma control_i + \varepsilon_i \quad (12)$$

where: M_i – mechanism variables such as yield (*YI*), soil carbon sequestration (*CS*), fertiliser input (*FI*) and energy use (*EI*).

We estimated all regressions by using the ordinary least squares method.

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Table 1. Input-output variables of MinDS-U (Minimum Distance to the Strong Efficient Frontier model with undesirable outputs)

Category	Variables	Mean	SD
Desirable output (y_{pk})	grain output (kg)	7 655.963 0	11 217.080 0
	carbon sequestration (kg)	7 977.621 0	11 680.700 0
Undesirable output (b_{qk})	carbon emission (kg)	885.367 6	1 366.163 0
Inputs (x_{ik})	fertiliser input (kg)	799.278 8	1 159.077 0
	capital input (USD)	526.753 5	1 312.390 0
	labour input (person)	2.028 4	0.676 8
	land input (hm^2)	0.468 3	0.670 8

Source: Authors' own elaboration

RESULTS AND DISCUSSION

CCE results. The average CCE across all sampled farmers was 0.592 6, with values ranging from 0.145 5 to 1, indicating substantial heterogeneity in efficiency levels. Sensitivity analyses confirmed the robustness of the estimated efficiencies. Detailed results are provided in Text S5 (ESM). As illustrated in Figure 2, the overall distribution of CCE was unimodal and left skewed, suggesting that most households operated below the efficiency frontier and that considerable potential for improvement remains. We observed clear distributional differences across tillage practices. RTS adopters had a right shifted and more concentrated distribution, indicating higher and more stable CCE, which is consistent with evidence that straw return stabilises soil structure and soil organic carbon accumulation with cereal rotation (Qin et al. 2024). NTS adopters had a bimodal pattern with a longer right tail, reflecting greater dispersion and polarisation in efficiency performance, which is consistent with the findings that the efficiency of NTS gains depend on scale, mechanisation and management standardisation (Mohammed et al. 2023). In contrast, CTS had a flatter distribution with a lower central tendency.

Table 2 complements the kernel density analysis by summarising the results of statistical tests examining differences in CCE across the three tillage practices. Although results from two sample *t*-tests did not indicate statistically significant mean differences between CT and CTS, the Kruskal-Wallis test results indicate marginally significant distributional differences among CTS, NTS and RTS. Overall, CT enhanced CCE directionally and reshaped its distribution by improving stability rather than generating large average gains.

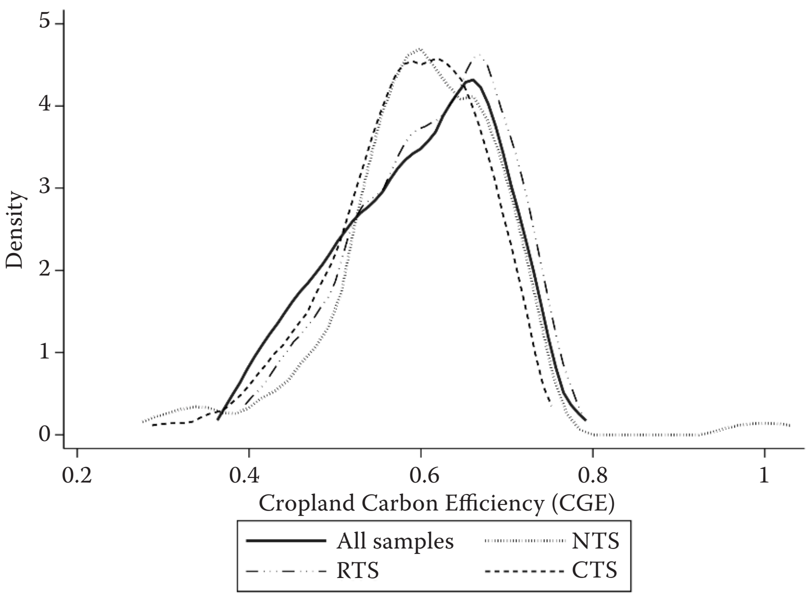

Figure 2. The kernel density distribution of sample farmers' CCE

CTS – farmers who adopted conventional tillage with straw returning; NTS – farmers who adopted no-tillage with straw returning; RTS – farmers who adopted reduced tillage with straw returning

Source: Authors' own elaboration

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Table 2. Cropland carbon efficiency (*CCE*) comparisons across tillage practices

Test	Groups	Mean (*CCE*) / χ^2	Test statistic	*P*-value	Significance
Two-sample *t*-test	NTS vs. CTS	0.603 6 vs. 0.587 6	–1.155 1	0.248 6	n.s.
	RTS vs. CTS	0.603 4 vs. 0.587 6	–1.144 17	0.149 9	n.s.
Kruskal–Wallis test	CTS / NTS / RTS	$\chi^2(2)$ = 5.914 0	–	0.052	10%

The two-sample *t*-tests compare *CCE* means between NTS or RTS and CTS; the Kruskal–Wallis test examines overall distributional differences among the three groups; CTS – farmers who adopted conventional tillage with straw returning; n.s. – not significant; NTS – farmers who adopted no-tillage with straw returning; RTS – farmers who adopted reduced tillage with straw returning

Source: Authors' own elaboration

Direct effects of tillage practices on CCE. Table 3 reports the benchmark Tobit regression results. Both NTS and RTS significantly enhanced CCE in the surveyed regions, and NTS had a larger marginal effect, suggesting that NTS is more conducive to improving CCE within the observed production conditions. The findings are consistent with evidence that CT enhances environmental performance through improved soil protection and input-use efficiency (Shakoor et al. 2024). Let the relatively more substantial gains from NTS than RTS diverge from earlier studies that emphasized the short-term advantages of reduced tillage (Lal et al. 2019; Van den Putte et al. 2010).

Endogeneity and robustness tests. To address potential endogeneity arising from nonrandom adoption of CT, we conducted a series of complementary tests. Results from Hausman tests indicated the presence of endogeneity (Table S4, ESM). We used propensity score matching and alternative matching algorithms to construct counterfactual comparisons between

Table 3. Results of benchmark regression

Variables	(1)	(2)	(3)
NTS	0.020 9* (0.011 4)	–	0.024 5** (0.011 5)
RTS	–	0.017 7* (0.009 9)	0.020 9** (0.010 0)
Age	0.000 6* (0.000 4)	0.000 6 (0.000 4)	0.000 6 (0.000 4)
Education	–0.001 2 (0.001 1)	–0.001 8 (0.001 1)	–0.001 5 (0.001 1)
Gender	–0.010 2 (0.017 6)	–0.013 8 (0.017 5)	–0.009 0 (0.017 6)
Risk preference	0.003 0 (0.004 5)	0.002 6 (0.004 5)	0.002 8 (0.004 5)
Cultivated land area	0.001 0** (0.000 4)	0.001 0** (0.000 4)	0.001 0** (0.000 4)
Land fragmentation	–0.013 7*** (0.004 8)	–0.013 4*** (0.004 8)	–0.013 4*** (0.004 8)
Irrigation	0.021 6** (0.009 0)	0.019 2** (0.009 0)	0.020 4** (0.009 0)
Land transfer	0.011 8 (0.010 7)	0.012 4 (0.010 7)	0.009 8 (0.010 8)
Off-farm labour	–0.011 2*** (0.003 2)	–0.011 9*** (0.003 2)	–0.012 2*** (0.003 2)
Agricultural income	0.015 6*** (0.004 3)	0.014 4*** (0.004 2)	0.016 0*** (0.004 3)
Whether Henan	–0.016 4* (0.008 9)	–0.024 0** (0.009 5)	–0.023 3** (0.009 5)
Whether Shaanxi	–0.051 8*** (0.009 7)	–0.053 9*** (0.009 8)	–0.054 5*** (0.009 8)
Constant	0.433 2*** (0.054 6)	0.462 7*** (0.053 0)	0.434 7*** (0.054 4)
Observations	633	633	633
Log likelihood	614.621 3	614.539 5	616.795 1
P-value	0.000 0	0.000 0	0.000 0
Pseudo R^2	–0.069 9	–0.069 7	–0.073 7

***, ** and *significance at the 0.01, 0.05, and 0.1 levels, respectively; standard errors in parentheses; *NTS* – farmers who adopted no-tillage with straw returning; *RTS* – farmers who adopted reduced tillage with straw returning

Source: Authors' own elaboration

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adopters and non-adopters. The estimated treatment effects indicated that both NTS and RTS increased CCE even after controlling for selection bias (Table S5, ESM). In addition, we introduced an instrumental variable capturing local policy inclination toward CT. The two-stage least squares estimate had results consistent with the benchmark findings (Table S6, ESM). Further robustness checks based on alternative variable definitions, treatment specifications and winsorised samples produced qualitatively similar results (Tables S7 and S8, ESM).

Mechanism analysis. Using the mechanism regression model, we further explored possible explanations for how CT practices improved CCE from the perspectives of input factors, yield and soil net carbon sink. The results are shown in Table 4.

Regarding input factors, NTS significantly reduced energy use by 0.487 units ($P < 0.01$), reflecting the elimination of ploughing and related mechanical operations and directly contributing to higher CCE (Bhattacharyya et al. 2022). In contrast, RTS significantly increased fertiliser use ($P < 0.1$) and had a tendency toward higher energy inputs, suggesting that the deeper rotary tillage required by RTS may partially offset its efficiency gains owing to increased power demands. These results indicate that the expected reduction in chemical fertiliser from straw returning has not been achieved, which may reflect farmers' output-oriented input decisions.

Furthermore, NTS and RTS significantly enhanced soil carbon sequestration at the 1% level, confirming a strong soil carbon sink mechanism. By reducing soil disturbance and preserving surface residues, both NTS and RTS protect soil organic carbon within aggregates and suppress microbial respiration, thereby lowering soil carbon emissions (Li et al. 2023). Straw returning further promotes carbon storage by providing substrates for microbial activity (Huang et al. 2024a). In terms of productivity, both tillage practices significantly enhance grain yields, findings consistent with those of Li et al. (2019). CT mitigated soil degradation, reduced water evaporation and improved soil moisture, fostering better conditions for wheat and maize growth, thereby increasing yield and then CCE.

Results from formal Sobel mediation tests helped confirm that input adjustment, soil carbon sequestration and yield effects served as statistically significant transmission channels, with indirect effects accounting for a substantial share of the total effect of tillage practices on CCE. Robustness checks based on alternative model specifications, control structures and sample subsets yielded consistent results. Furthermore, NTS and RTS significantly enhanced soil carbon sequestration at the 1% level, confirming a strong soil carbon sink mechanism. By reducing soil disturbance and preserving surface residues, both NTS and RTS protected soil organic carbon within aggregates and suppressed microbial respiration, thereby lowering soil carbon emission variables and yielding consistent results. Detailed procedures are provided in Text S3 (ESM).

Heterogeneity analysis. The effects of tillage practices on CCE varied substantially across farmer characteristics, reflecting differences in resource endowments and livelihood strategies. Farm size played a key role. When we divided the sample into terciles by cultivated area, the effect of NTS strengthened with increasing farm size. NTS was slightly negative for small-scale

Table 4. Results of the mechanism test

Variables	*FI*		*EI*		*YI*		*CS*	
NTS	0.086 5 (0.081 9)	–	−0.487 3*** (0.053 4)	–	0.121 0** (0.059 0)	–	0.541 6*** (0.132 1)	–
RTS	–	0.113 4* (0.062 4)	–	0.088 4* (0.049 4)	–	0.163 9** (0.051 1)	–	1.608 5*** (0.096 9)
Control variables	controlled		controlled		controlled		controlled	
Constant	2.394 0*** (0.344 1)	2.527 1*** (0.333 3)	−0.196 6 (0.255 6)	−0.748 4*** (0.263 4)	3.813 0*** (0.282 3)	4.000 8*** (0.272 6)	−1.991 7** (0.631 9)	−0.911 4* (0.516 9)
Observations	633	633	633	633	633	633	633	633

***, ** and *significance at the 0.01, 0.05, and 0.1 levels, respectively; standard errors in parentheses

CS – carbon sequestration; *EI* – energy use; *FI* – fertiliser input; *NTS* – farmers who adopted no-tillage with straw returning; *RTS* – farmers who adopted reduced tillage with straw returning; *YI* – yield

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farmers but positive and statistically significant for larger farms, consistent with the role of mechanisation and standardised management in realising its efficiency gains (Otsuka et al. 2016). In contrast, RTS had a positive and significant effect among small-scale farmers, but its effect diminished as farm size increased, suggesting that RTS is more compatible with labour-intensive and fragmented production systems (Table S12, ESM).

Farmer human capital further conditioned these effects. When we grouped farmers by education, RTS had a stronger effect among more-educated farmers, whereas NTS was more effective for less-educated farmers (Table S13, ESM). This pattern reflects differences in labour allocation and off-farm opportunities, as better-educated farmers faced tighter on-farm labour constraints and therefore benefitted more from RTS, whereas less-educated farmers devoted more time to farming and could exploit the monitoring-intensive advantages of NTS (Ruzzante et al. 2021). Age-based heterogeneity results showed that CT significantly enhanced CCE among older farmers, whereas the effects were weaker and statistically not significant for younger farmers. Although older farmers generally had a lower propensity to adopt new technologies, their stronger dependence on the land and their greater emphasis on conservation practices may explain this result (Osman and Bergtold 2025).

Overall, these findings indicate that the effectiveness of CT depends critically on farm scale, labour availability and livelihood strategies. The scale dependence of NTS aligns with evidence concerning mechanisation and standardisation effects (Otsuka et al. 2016; Mohammed et al. 2023), whereas the suitability of RTS for smallholders reflects its lower management requirements. More broadly, the heterogeneous returns to tillage practices were consistent with prior evidence that the economic and environmental benefits of agricultural technologies vary across farmer groups (Mohammed and Abdulai 2022). The patterns were also consistent with the visual evidence in Figure 3.

CONCLUSION

This study is based on the household data from 633 wheat–maize rotation farming households in 2020. Using the MinDS-U model, we analysed the differential effects of NTS, RTS and CTS on CCE on the basis of these data, and then we further explored the underlying influence mechanisms and heterogeneity effects. We drew three main conclusions as follows. First, the average CCE for all households in the sample region was 0.592 6, which means there is 40.74% room for improvement if technical inefficiencies were eliminated. Second,

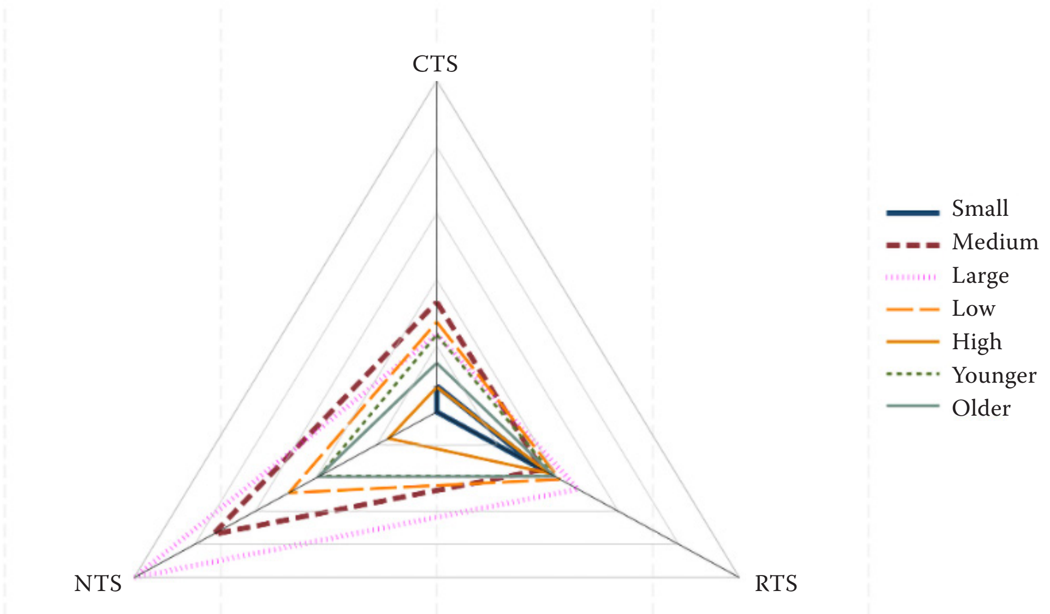

Figure 3. Integrated radar chart of heterogeneous impacts of tillage practices on cropland carbon efficiency (CCE)

CTS – farmers who adopted conventional tillage with straw returning; NTS – farmers who adopted no-tillage with straw returning; RTS – farmers who adopted reduced tillage with straw returning

Source: Authors' own elaboration

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the adoption of NTS and RTS was positively associated with CCE, and NTS had a stronger effect than RTS. Mechanism testing results revealed that NTS was linked to higher yields, improved soil carbon sequestration and reduced energy use, contributing to lower emissions. In contrast, RTS was associated with increased yields, carbon sequestration and higher fertiliser and energy inputs, which may have offset some of its efficiency gains. Finally, heterogeneity results indicated that NTS performed better among larger farms and older farmers, whereas RTS was relatively more beneficial for smallholders and better-educated farmers.

Policy and practical implications. The findings indicate that CT, particularly NTS and RTS, can enhance CCE, although their effectiveness depends on farmer characteristics and resource endowments. NTS is more suitable for households with greater labour availability and capacity for long-term management, whereas RTS offers a more feasible option for labour-constrained farmers by delivering yield gains with moderate input adjustments. These differences highlight the need for differentiated extension strategies rather than uniform promotion. From a policy perspective, targeted subsidies, access to specialised machinery and capacity-building programmes are essential to support NTS adoption, whereas RTS requires complementary measures to manage fertiliser and energy use and avoid rebound effects. At the regional level, integrating CT with mechanisation services, straw returning infrastructure and carbon accounting systems can help balance yield, input use and carbon emissions, thereby supporting sustainable agricultural transitions aligned with China's dual carbon objectives.

Limitations and future outlook. In this study, we relied on cross-sectional production data from the 2020 cropping cycle; we therefore did not capture temporal dynamics or policy effects introduced after 2020. Moreover, although the MinDS-U model is suitable for measuring CCE, we estimated the carbon emissions and sequestration by using standard coefficients rather than field-based measurements, which may not fully reflect site-specific variations. Future research could address these limitations by using multiyear panel data to capture dynamic effects and improve external validity. Carbon accounting could be refined through field-based measurements of soil processes. From a methodological perspective, integrating frontier-based approaches may further enrich efficiency analysis, as demonstrated in related applications concerning energy taxation and cleaner production (Hamidoğlu et al. 2025).

Acknowledgement statement: The authors would like to thank the anonymous referees for their helpful suggestions and corrections on the earlier draft of our paper. All authors contributed to the study conception and design. Methodology, data curation, conceptualization, formal analysis, writing -original draft and review & editing were performed by Yu Wang. Methodology, software, data curation, and critical revision of the article were performed by Boqian Wang. Conceptualization, supervision, project administration and writing-review & revision were performed by Xiuguang Bai. All authors critically revised the manuscript and approved of the final version.

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Received: March 4, 2025
Accepted: January 30, 2026