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

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Table S1. Comparison of related studies on cropland carbon efficiency

Author(s), year	Method	Focus	Key points	Limitations
Cheng et al. (2011)	single-factor method	agricultural carbon efficiency	measured carbon efficiency via output/emission ratio	lacks factor interactions
Iglesias et al. (2013)	experiment	orchard carbon fixation	compared photosynthetic fixation vs. system emissions	neglect farmers' behaviour
Luo et al. (2020)	SBM	cultivated land use efficiency	spatiotemporal variations of CLUE and factors affecting	neglect carbon sinks
Chen et al. (2021)	a three-stage SBM-DEA model with non-point source pollution and CO_2 emissions	agricultural green total factor productivity	AGTFP is overestimated without accounting for environmental constraints	neglect carbon sinks
Wu et al. (2022)	SBM	carbon emission efficiency of crop production	spatial interaction positively affected the convergence of the carbon-emission efficiency	provincial macro level; neglects the soil carbon sink
Qiao et al. (2023)	SBM	net carbon sink efficiency	a spatial spillover effect existed between urbanization and net carbon sink efficiency across counties	county macro level; neglects soil carbon sink
Guan et al. (2023)	"system-of-systems" solution	quantifying field-level agricultural carbon outcomes	proposed integrated sink-emission framework	lacks empirical support
Ding et al. (2025)	field experiment	RT on SOC and CO_2	RT increases SOC, lowers CO_2 emissions	experimental, not behavioural
Meng et al. (2024)	meta-analysis	GHG under conservation tillage	CT reduces N_2O and CO_2 emissions	no micro/farmer-level dynamics
Freitag et al. (2024)	carbon footprint analysis	conservation agriculture emissions	CT lowers emissions footprint	no integration of sequestration
This paper	MinDS-U	how tillage affects CCE; mechanisms	integrates emissions and sequestration at the micro-level CCE	regional focus

AGTFP – Agricultural Green Total Factor Productivity; CCE – cropland carbon efficiency; CT – conventional tillage; DEA – Data Envelopment Analysis; GHG – greenhouse gases; MinDS-U – Minimum Distance to the Strong Efficient Frontier model with undesirable outputs; RT – reduced tillage; SBM – lack-Based Measure; SOC – soil organic carbon

Source: Authors' own elaboration

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Table S2. Descriptive statistics of variables

Variables		Definition	Mean	SD
Core independent variable	*tillage practices*	1 = adopt NTS, 0 = not adopt NTS 1 = adopt RTS, 0 = not adopt RTS	0.121 6 0.191 2	0.327 1 0.393 5
Household head characteristics	*age*	actual age in 2020	60.176 9	10.235 7
	gender	1 = male, 0 = female	0.966 8	0.204 0
	education	years of schooling of the head of household	6.996 8	3.354 1
	risk preference	1 = risk averse, 2 = risk neutral, 3 = risk preferred	1.737 8	0.813 7
Land operation characteristics	*cultivated land area*	household cultivation area (ha)	0.485 6	0.704 8
	irrigation	1 = surface water, 2 = groundwater	1.922 6	0.415 7
	land fragmentation	number of land parcels (graded 1–5, where 1 = 1; 2 = 2; 3 = 3; 4 = 4; 5 = 5 and above)	2.015 8	0.748 2
	land transfer	1 = with land transfers, 0 = without land transfers	0.143 8	0.351 1
Farm household characteristics	*off-farm labour*	number of non-farm labours	1.562 4	1.141 7
	agricultural income	household agricultural income (logarithmic)	9.309 3	1.037 2
Regional variables	*whether located in Henan province*	1/0	0.363 3	0.481 3
	whether located in Shaanxi province	1/0	0.290 7	0.454 4
Mechanism variables	*fertiliser inputs*	amount of fertiliser inputs of wheat-corn rotation in 2020 (log)	6.265 3	0.872 4
	energy inputs	amount of diesel fuel inputs of wheat-corn rotation in 2020 (log)	3.590 6	0.800 7
	yield	total yield of wheat-corn rotation in 2020 (log)	8.529 9	0.856 3
	net soil carbon sink	soil carbon sinks minus soil carbon emissions in wheat-corn rotation in 2020 (log)	–2.993 2	4.640 7

NTS – no-tillage with straw returning; RTS – reduced tillage with straw returning
Source: Authors' own elaboration

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TEXT S1. ESTIMATION OF CARBON EMISSIONS

Estimation of carbon emissions. This paper focuses on two categories: direct carbon emissions caused by agricultural inputs, sowing, harvesting, and farming during wheat and corn production, and soil carbon emissions. The estimation formula for cropland carbon emissions is as follows:

$$C_o = \sum(C_t + C_l) = \sum(T_i \times \delta_i + C_i \times \theta_i) \tag{1}$$

where: C_0 – the total carbon emissions from cropland (kg C); C_t – the carbon emission in the process of crop production, specifically including the carbon emission directly generated by chemical fertiliser input, pesticide input, agricultural machinery use, irrigation and tilling, etc; C_l – the amount of soil carbon emissions, mainly referring to the amount of greenhouse gases produced by soil respiration (converted to C); T_i – the input quantity of each carbon emission source (hm^2 or kg); δ_i – the carbon emissions coefficient caused by T_i, soil carbon emissions include emissions from soil respiration and the release of organic carbon due to soil carbon pool destruction caused by tillage practices; C_i – the area of cultivated land (hm^2); θ_i – the carbon emission coefficient per unit of cultivated land (kg/hm^2).

The carbon emission coefficients are shown in Table S3.

Table S3. Carbon emission coefficients

Carbon source	Activities	C emission coefficient	Unit	Reference source
Agricultural materials	diesel fuel	0.592 7	kg/kg	IPCC
	irrigation	25.000 0	kg/hm^2	Dubey
	chemical fertiliser	0.895 6	kg/kg	IABCAU
	pesticide	4.934 1	kg/kg	ORNL
	agricultural plastic film	5.180	kg/kg	IREEA
Soil carbon emissions	ploughing	3.126	kg/hm^2	Wu et al. (2007)
	no-tillage	2.805 2	kg/hm^2	
	minimum tillage	2.954 1	kg/hm^2	

ORNL – Oak Ridge National Laboratory; IREEA – Institute of Resource, Ecosystem and Environment of Agriculture of Nanjing Agricultural University; IPCC – Intergovernmental Panel on Climate Change; IABCAU – College of Agronomy and Biotechnology of China Agricultural University, U.S. Department of Agriculture; Dubey – Dubey Laboratory
Source: Authors' own elaboration

TEXT S2. ESTIMATION OF CARBON SINK

Estimation of carbon sink. The carbon sink of cropland mainly includes the crop carbon sink and soil carbon sink. Crop carbon sink refers to the process in which crops convert carbon in the air and soil into primary agricultural products through photosynthesis during their growth. Soil carbon sink is the process of fixing and storing soil organic carbon through microbial activity during the growth of cereal crops, which is obtained by multiplying the carbon sink coefficient by the cultivated land area. The specific calculation is as follows:

$$C_s = \sum_i^n (C_i + C_h) = \sum_i^n [C_f \times Y_i \times (1 - W_i) \times (1 + R_i)] / H_i + \sum_i^n C_m \times A_m \tag{2}$$

Where: C_s – the total carbon sink in cropland; C_i – the carbon sink in crop *i*; C_h – the carbon sink in soil; C_f – the carbon uptake rate; Y_i – the yield of crop *i*; W_i – the moisture content of crop *I*; R_i – the plant root-crown ratio; H_i – the economic coefficient of crop *I*; C_m – the carbon sink coefficient of cultivated land; A_m – the cultivated area (hm^2). The corresponding coefficients referring to the research results of Wang et al. (2022). According to the experimental results of Wu et al. (2007), compared to conventional tillage, reduced tillage and no-tillage increase soil surface carbon sink by an average of 4.34 kg/hm^2 and 2.04 kg/hm^2 per year, respectively.

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Table S4. Results of endogenous test

Variables	NTS			RTS		
	IV	OLS	Difference	IV	OLS	Difference
NTS	0.169 8** (0.069 9)	0.020 5 (0.016 0)	0.149 4 (0.062 8)	–	–	–
RTS	–	–	–	0.148 6** (0.061 5)	0.014 9 (0.009 9)	0.133 7 (0.055 0)
Constant	0.251 0** (0.105 5)	0.427 6*** (0.062 3)	–	0.492 4*** (0.068 2)	0.455 9*** (0.060 5)	–
Hausman test		5.650 0			5.900 0	
P-value		0.017 5			0.015 1	

***, **, and *significance at the 0.01, 0.05, and 0.1 levels, respectively; standard errors in parentheses; IV – instrumental variable method; NTS – no-tillage with straw returning; OLS – ordinary least squares; RTS – reduced tillage with straw returning

Source: Authors' own elaboration

Table S5. Results of PSM

Variables	Matching methods	Average treatment effect	*t*-test value
NTS	spline matching	0.021 3* (0.012 8)	1.664 1
	K-nearest neighbour matching	0.025 1** (0.012 3)	2.040 7
	mean	0.023 2	–
RTS	spline matching	0.018 3* (0.010 3)	1.776 7
	K-nearest neighbour matching	0.019 3* (0.011 0)	1.754 5
	mean	0.018 8	–

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

Source: Authors' own elaboration

Table S6. Results of two-stage least squares estimation

	First-stage		Second-stage	
	NTS	*RTS*	*CCE*	*CCE*
Policy preference	0.183 4*** (0.043 4)	0.251 2*** (0.052 5)	–	–
NTS	–	–	0.148 9** (0.074 5)	
RTS	–	–	–	0.108 7** (0.053 6)
Control variables	controlled	controlled	controlled	controlled
Constant	0.523 8*** (0.148 3)	–0.411 4** (0.179 7)	0.324 8*** (0.064 2)	0.447 6*** (0.048 8)
First-stage *F*-value	17.895 0***	23.395 9***	–	–
Non-identifiable test	LM statistic		17.592***	22.321***
Weak instrumental variable test	Cragg-Donald Wald *F* statistic		17.895	22.881
	Srock-Yogo F		16.38 (10%)	16.38 (10%)

***, **, and *significance at the 0.01, 0.05, and 0.1 levels, respectively; standard errors in parentheses; CCE – cropland caron efficiency; NTS – no-tillage with straw returning; RTS – reduced tillage with straw returning

Source: Authors' own elaboration

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Table S7. Results of new explanatory variables and winsorised variable

Variables	New explanatory variables			Winsorised variable		
	(8)	(9)	(10)	(11)	(12)	(13)
NTS	0.066 6*** (0.011 5)	0.037 5** (0.014 1)	–	0.019 6** (0.008 9)	0.016 7* (0.008 8)	–
RTS	0.182 3*** (0.010 0)	–	0.174 2*** (0.010 1)	0.017 1** (0.007 7)	–	0.014 6* (0.007 6)
Control variables	controlled	controlled	controlled	controlled	controlled	controlled
Constant	0.364 2*** (0.054 7)	0.351 4*** (0.067 8)	0.441 5*** (0.054 5)	0.451 7*** (0.041 9)	0.450 5*** (0.042 0)	0.474 2*** (0.040 8)
Log likelihood	587.392 0	454.741 2	571.009 6	799.886 2	797.437 4	797.446 0
P-value	0.000 0	0.000 0	0.000 0	0.000 0	0.000 0	0.000 0

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

Source: Authors' own elaboration

Table S8. Results of new independent variable

Variables	New independent variable
CT	0.022 4*** (0.008 1)
Control variables	Controlled
Constant	0.437 5*** (0.053 2)
Log likelihood	616.762 8
P-value	0.000 0

***significance at the 0.01 level; standard errors in parentheses; *CT* – conventional tillage

Source: Authors' own elaboration

TEXT S3. SENSITIVITY TEST FOR MECHANISM ANALYSIS

Table S9. Sobel test results for mechanism

Mechanism	Tillage	a	b	Sobel		Indirect effect
		Tillage → M	M → CCE	*Z*-value	*P*-value	
FI	*NTS*	0.086 6	–0.031 9***	–1.160 0	0.244	–0.002 8
	RTS	0.113 4*	–0.032 2***	–1.690 0*	0.092	–0.003 7*
EI	*NTS*	–0.487 3***	0.049 7***	–4.500 0***	0.000 0	–0.024 2***
	RTS	0.088 4*	0.038 2***	1.650 0*	0.099	0.003 4*
YI	*NTS*	0.121 0**	0.085 2***	2.010 0**	0.044	0.010 3**
	RTS	0.163 9***	0.085 7***	3.070 0***	0.002	0.014 0***
CS	*NTS*	0.541 6***	0.007 8**	1.790 0*	0.074	0.004 3*
	RTS	1.608 5***	0.008 4*	1.770 0*	0.076	0.013 5*

***, **, and *significance at the 1%, 5%, and 10% levels, respectively; coefficient *a* represents the effect of tillage on the mechanism variable (Tillage → M), coefficient *b* represents the effect of the mechanism variable on cropland carbon efficiency (M → CCE); the Sobel *Z*-value and *P*-value indicate the significance of the indirect effect ($a \times b$); CS – carbon sequestration; EI – energy use; FI – fertiliser input; YI – yield

Source: Authors' calculation based on survey data, 2020

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Table S10. Sensitivity test for mechanism analysis

Variables	*FI*		*EI*		*YI*		*CS*	
NTS	0.079 5 (–0.067 8)	–	–0.482 2*** (–0.054 7）	–	–0.482 2*** (–0.054 7)	–	0.440 9*** (–0.116 3)	–
RTS	–	0.098 4* (–0.058 9)	–	0.095 0* (–0.050 3)	–	0.095 0* (–0.050 3)	–	1.589 8*** (–0.080 0)
Control variables	Controlled		Controlled		Controlled		Controlled	
Constant	2.342 7*** (–0.324 5)	2.463 3*** (–0.314 4)	–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)

***, **, and *significance at the 0.01, 0.05, and 0.1 levels, respectively; standard errors in parentheses; *CS* – soil carbon sequestration; *EI* – energy use; *FI* – fertiliser input; *NTS* – no-tillage with straw returning; *RTS* – reduced tillage with straw returning; *YI* – yield

Source: Authors' own elaboration

In addition, we further strengthened the mechanism analysis by conducting multiple sensitivity tests to quantitatively assess how NTS and RTS influence CCE through changes in fertiliser use, energy input, yield, and soil carbon sequestration. These additional analyses ensure that the identified mechanisms are not artifacts of model specification or sample composition, but represent robust agronomic and behavioural pathways. Specifically, for fertiliser input, we employed propensity score matching (PSM) to address potential selection bias. For energy input, we restricted the sample to Henan and Shaanxi provinces to control for terrain-related heterogeneity. For yield effects, we introduced climatic controls—including rainfall, temperature, and sunshine—to rule out weather-induced confounding. For soil carbon sequestration, we redefined the treatment variable as a unified "conservation tillage" dummy combining NTS and RTS to test classification sensitivity. Collectively, these sensitivity analyses confirm that the three mechanism pathways (input adjustment, yield enhancement, and carbon sequestration) remain statistically robust across alternative model specifications, control structures, and sample subsets. This comprehensive validation provides strong quantitative support for the credibility of the mechanism framework linking conservation tillage to improved CCE.

Table S11. More sensitivity test for mechanism analysis

Variables	*FI*		*EI*		*YI*		*CS*
	PSM: Average Treatment Effect		Change the sample range		Add control variables		Replace the definition of the tillage variable
CT	–		–		–		0.020 3** (0.009 2)
NTS	0.086 3 (0.128 8)		–0.347 7*** (0.075 5)	–	0.120 2** (0.058 5)		–
RTS	–	0.229 4** (0.095 3)	–	0.092 9* (0.051 4)	–	0.157 7*** (0.050 6)	
Control variables	controlled		controlled		controlled		controlled
Climatic controls	–		–		controlled		–
Constant	–		–0.705 2** (0.326 3)	–1.080 1*** (0.322 3)	–	9.344 1*** (2.078 7)	–

***, **, and *significance at the 0.01, 0.05, and 0.1 levels, respectively; standard errors in parentheses; *CS* – soil carbon sequestration; *CT* – conventional tillage; *EI* – energy use; *FI* – fertiliser input; *NTS* – no-tillage with straw returning; *RTS* – reduced tillage with straw returning; *YI* – yield

Source: Authors' own elaboration

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TEXT S4. HETEROGENITY ANALYSIS

Table S12. Results of heterogeneity in farm size

Variables	Small scale	Medium scale	Large scale
NTS	–0.004 6 (0.015 2)	0.050 1** (0.022 0)	0.058 9** (0.026 3)
RTS	0.031 6* (0.016 1)	0.003 4 (0.018 0)	0.017 8 (0.017 8)
Control variables	Controlled	Controlled	Controlled
Constant	0.419 3*** (0.091 3)	0.253 9** (0.123 4)	0.335 5*** (0.126 7)
Sample size	280	176	177
Log likelihood	291.144 6	187.031 6	166.012 9
P-value	0.000 1	0.110 3	0.000 0

***, **, and *significance at the 0.01, 0.05, and 0.1 levels, respectively; standard errors in parentheses; *NTS* – no-tillage with straw returning; *RTS* – reduced tillage with straw returning
Source: Authors' own elaboration

Table S13. Results of heterogeneity in human capital

Variables	High educated	Low educated	Older	Younger
NTS	0.020 8 (0.020 2)	0.026 9* (0.013 9)	0.029 8* (0.015 7)	0.021 7 (0.016 9)
RTS	0.026 1* (0.014 9)	0.015 0 (0.013 6)	0.026 5* (0.015 0)	0.016 4 (0.013 4)
Control variables	controlled	controlled	controlled	controlled
Constant	0.353 9*** (0.075 3)	0.418 2*** (0.074 3)	0.446 8*** (0.087 2)	0.484 2*** (0.060 2)
Sample size	261	372	308	325
Log likelihood	268.889 8	358.798 3	300.517 8	322.503 6
P-value	0.000 0	0.001 8	0.000 0	0.001 4

*** and *significance at the 0.01 and 0.1 levels, respectively; standard errors in parentheses; *NTS* – no-tillage with straw returning; *RTS* – reduced tillage with straw returning
Source: Authors' own elaboration

TEXT S5. SENSITIVITY ANALYSIS OF EFFICIENCY ESTIMATES

Table S14. Sensitivity analysis of efficiency estimates under jackknife tests

Specification	Mean efficiency	Δ mean%	Spearman's ρ
Baseline	0.593		
Var1	0.598	0.98	0.821***
Var2	0.587	–0.91	0.468***
Var3	0.595	0.48	0.782***
Var7	0.781	31.88	0.269***
Var4	0.587	–0.97	0.430***
Var5	0.596	0.51	0.645***
Var6	0.592	–0.04	0.247***

***significance at the 0.01 level; Var1–Var7 report jackknife tests by sequentially excluding the top 7 frontier DMUs; Δ mean% denotes the relative change in mean efficiency compared with the baseline
Source: Authors' own elaboration

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Table S15. Re-estimation excluding Decision-Making Unit DMU344

	(1)	(2)	(3)
NTS	0.021 1* (0.011 4)	–	0.024 9** (0.011 5)
RTS	–	0.018 7* (0.009 9)	0.022 0** (0.010 0)
Control variables	controlled	controlled	controlled
Constant	0.426 4*** (0.054 9)	0.455 7*** (0.053 2)	0.426 9*** (0.054 7)
n	632	632	632

***, **, and *significant at the 0.01, 0.05, and 0.1 levels, respectively; standard errors in parentheses; *NTS* – no-tillage with straw returning; *RTS* – reduced tillage with straw returning
Source: Authors' own elaboration

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