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RESEARCH ARTICLE

Impact mechanisms and pathways of agricultural socialized services on agricultural green production in China under its dual-carbon goals

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SUPPLEMENTARY MATERIALS

This study assumed the decision-making unit (DMU) has: an input vector: $\in RN_+^N$ (N-dimensional non-negative real space); a desirable output vector: $y \in RN_+^M$ (M-dimensional non-negative real space); an undesirable output vector: $b \in RN_+^I$ (I-dimensional non-negative real space). Then the production technology set $P^t(x^t)$ is then formally defined as:

$$P^t(x^t) = \left\{ (y,b) \in \mathbb{R}_+^M \times \mathbb{R}_+^I \left| \begin{array}{ll} \sum_{k=1}^K z_k\, y_{km}^t \geq y_m, & (m = 1,\ldots,M) \\ \sum_{k=1}^K z_k\, b_{ki}^t \leq b_i, & (i = 1,\ldots,I) \\ \sum_{k=1}^K z_k\, x_{kn}^t \leq x_n, & (n = 1,\ldots,N) \\ b_i \leq \bar{b}_i(x^t), & (i = 1,\ldots,I) \\ z_k \geq 0, & (k = 1,\ldots,K) \end{array} \right. \right\} \quad \text{(S1)}$$

where, M is the dimension of desirable outputs, *I* is the dimension of undesirable outputs, *N* is the dimension of inputs; K corresponds to the number of intensity variables $(Z_k, k = 1,\ldots,K)$, t is the time period; the production technology incorporates an upper bound constraint for undesirable outputs as $b_i^t(x^t)$, which ensures weak disposability of bad outputs and environmental regulation compliance. The directional distance function is formally defined as: $\vec{D}_0(x,y,b;g) = sup\{\beta: (y,b) + \beta g \in P(x)\}$, where the direction vector $g = (y,-b)$ specifies proportional expansion of desirable outputs $(+y)$ or proportional reduction of undesirable outputs $(-b)$. The technically enhanced Malmquist-Luenberger index is defined as:

$$ML^s = \left[\frac{1+\vec{D}_0^t(x^t,b^t;y^t,-b^t)}{1+\vec{D}_0^{t+1}(x^{t+1},y^{t+1},b^{t+1};y^{t+1},-b^{t+1})}\right] \quad \text{(S2)}$$

where, *S* is the time period vector, which can be further decomposed into the product of green technical efficiency change and green technological change. The former embodies the catch-up effect, indicating the distance between the DMU and the production frontier, reflecting improvements in the resource allocation of the DMU, management practices and organizational methods. The latter represents the frontier-shift effect, which shows the movement of the production frontier itself, reflecting technological innovation driven by external technology adoption and internal R&D efforts by the DMU. To avoid arbitrariness in selecting the reference technology frontier, the Malmquist-Luenberger index is calculated as the geometric mean across two periods. The directional distance function $\vec{D}_0^s(x_0^h, y_0^h, b_0^h; y_0^h, -b_0^h)$ can be computed through Eq. (S3).

$$
\begin{aligned}
max\beta = \vec{D}_0^s(x_0^h, y_0^h, b_0^h; y_0^h, -b_0^h) & \\
s.t. & \\
\textstyle\sum_{k=1}^{K} z_k\, y_{skm} \geq y_{h0m} + \beta y_{h0m}, & \quad \forall m = 1, \ldots, M \\
\textstyle\sum_{k=1}^{K} z_k\, b_{ski} \leq b_{h0i} - \beta b_{h0i}, & \quad \forall i = 1, \ldots, I \\
\textstyle\sum_{k=1}^{K} z_k\, x_{skn} \leq \bar{x}_{h0n}, & \quad \forall n = 1, \ldots, N \\
b_{h0i} - \beta b_{h0i} \leq b_i^s(x_{h0}), & \quad \forall i = 1, \ldots, I \\
z_k \geq 0, & \quad \forall k = 1, \ldots
\end{aligned}
\tag{S3}
$$

where, β is the objective function value and $h = (t, t+1)$ is the time period vector.

To ensure robust measurement of agricultural green production at the household level, a dual measurement strategy was used following Cheng et al.[1]: first, deriving AGTFP data using subjective environmental evaluation scores from virtual household heads (agricultural account-keepers) as undesirable output variables; second, calculating alternative AGTFP estimates (denoted by AGTFP_a) by matching provincial-level objective indicators including agricultural chemical oxygen demand, total nitrogen and total phosphorus through provincial codes. Both AGTFP measures serve as proxy variables for micro-level agricultural green production. Following the methodological framework developed by Oh[2], the detailed input and output indicator system for measuring household-level agricultural green production is summarized in Table S2.

Table S1 gives the sample attrition analysis, comparing mean values of key baseline (2014) variables across the full sample, the balanced panel, and the attrited sample. Balance tests indicate statistically insignificant differences between groups for both the core variable agricultural socialized services and all the control variables (all p-values > 0.05). These findings imply that attrition likely occurred at random and the retained households remain broadly representative of the original sample in terms of baseline characteristics. It is therefore concluded that sample attrition does not substantially threaten the validity of the core results.

Table S1 Sample attrition analysis

Variable (baseline 2014)	Full sample (n = 12,458)	Balanced panel (n = 7794)	Attrited sample (n = 4664)	P value
Agricultural socialized service	7.26	7.17	7.27	0.0834
Village to county distance	28.0	28.0	28.3	0.0962
Village economic condition	3.74	3.75	3.73	0.133
Village per capita income	2.75	2.89	2.68	0.0804
Presence of polluting enterprises	0.319	0.302	0.320	0.125

Note: Cumulative attrition rate of 37% calculated as (12,458 – 7794) / 12,458.

Table S2 Agricultural green total factor productivity input-output indicators

Primary indicator dimension	Secondary indicator dimension	Specific variables and description	Unit
Input indicators	Capital	Total liquidity capital and fixed capital inputs in agricultural production	yuan
	Labor	Family members engaged in agricultural production in past 12 months (excluding hired labor)	person
	Land resources	Total area of contracted and rented land	mu
Desired output indicators	Total agricultural output	Total value of agricultural products, livestock and byproducts (including self-consumed)	yuan
Undesired output indicators	Agricultural non-point source pollution	Equivalent emissions of chemical oxygen demand	ton
		Equivalent emissions of total nitrogen	ton
		Equivalent emissions of total phosphorus	ton
	Subjective pollution perception	Household head perception of environmental pollution severity (0 = not severe, 10 = very severe)	none

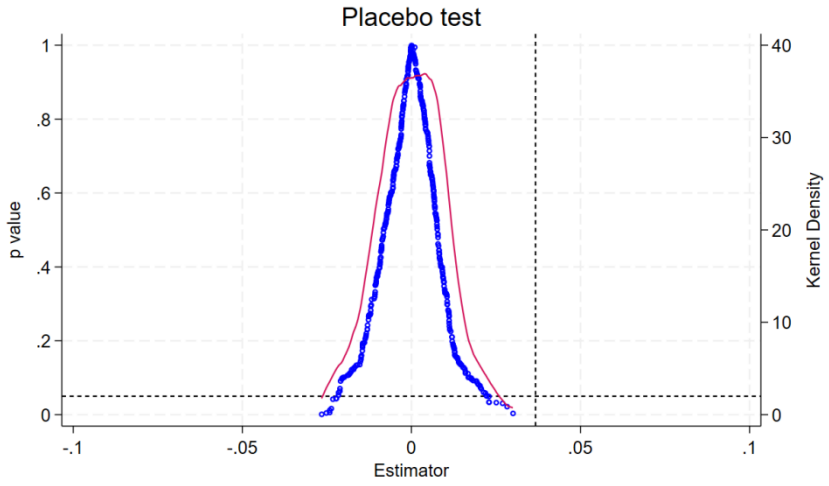

Fig. S1 Placebo test result.

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