

CROP-SYSTEM RESILIENCE AND FERTILIZER-USE INTENSITY IN RICE-WHEAT-MAIZE PRODUCTION UNDER REGIONAL DIGITAL ECONOMIC DEVELOPMENT IN CHINA

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Abstract

Resilience of crop production depends on productivity, water and mechanical capacity, crop diversity, chemical-input pressure and resistance to natural-disaster loss. This study evaluated rice-wheat-maize production systems in 30 Chinese provincial-level regions during 2014-2021. A six-indicator crop production system resilience (CPSR) index was constructed using entropy weights on 233 complete province-year observations. Two-way fixed-effects models showed no detectable average association between regional digital economy development and CPSR ($\beta = -0.0150$, $p = 0.638$), and none of six component associations survived false-discovery-rate adjustment. In a plant-input analysis, a one-standard-deviation increase in digital-finance usage depth was associated with 57.5 kg/ha lower fertilizer intensity ($p = 0.0148$); the direction persisted across sample, lag, outlier and influence checks but weakened under province-specific trends. Digital development was therefore more clearly related to fertilizer-use intensity than to short-run system-wide crop resilience.

Introduction

Crop production resilience concerns the capacity of a production system to maintain useful functions under climatic, resource and management pressures rather than simply obtaining a high yield in a favourable year. In rice-, wheat- and maize-based systems, resilience is jointly shaped by productive performance, irrigation capacity, operational resources, crop structure, chemical-input pressure and the severity of crop loss after natural disasters. This systems view is consistent with broader resilience concepts that integrate performance, adaptation and shock response (Tendall *et al.* 2015, Ansah *et al.* 2019, Darnhofer 2021). It is also relevant to recent plant-production research published in Bangladesh Journal of Botany, where irrigation management, crop-pattern stability and nutrient management are treated as important determinants of sustainable crop performance (Kumar and Swain 2025, Fang *et al.* 2026, Huang 2026).

China provides a useful setting for examining crop-system resilience because major crop production occurs across large differences in water availability, mechanization, cropping structure and disaster exposure. During the same period, fertilizer management became an important sustainability concern. Lower fertilizer intensity can indicate reduced chemical-input pressure, although it should not be interpreted as improved fertilizer-use efficiency unless yield response is also demonstrated. Recent crop studies show that nutrient management can materially change yield and resource-use outcomes (Sujatha *et al.* 2025), while work on cultivated-land transition and crop mapping highlights the importance of spatially differentiated production conditions (Yang *et al.* 2025, Cao 2026, Fang *et al.* 2026).

Regional digital development may alter this production environment by reducing information and transaction costs, improving access to financial services and changing the timing of input purchases. Digital finance has been associated with agricultural green productivity and fertilizer

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reduction (Li *et al.* 2023, Liu *et al.* 2026), and recent Chinese studies report positive or nonlinear associations between digitalization and agricultural or food-production resilience (Luo *et al.* 2025, Hou *et al.* 2025, Huang *et al.* 2026, Ji *et al.* 2026). These findings, however, do not establish that broad digital-economy development will translate rapidly into plant-production resilience because irrigation systems, mechanization stocks and crop structure adjust more slowly than information or input-management decisions.

The present study therefore places plant production at the centre of the analysis. It first constructs a crop production system resilience (CPSR) index for provincial rice-wheat-maize production using yield, effective irrigation-area ratio, mechanization intensity, crop diversity, fertilizer intensity and disaster resistance. It then asks whether regional digital economy development is associated with the composite index or its individual agronomic components, and whether digital-finance usage depth is more clearly associated with fertilizer-use intensity. The analysis is observational; the objective is to identify robust statistical associations and their agronomic interpretation rather than to claim causal effects.

Materials and Methods

The panel covered 30 provincial-level regions of mainland China from 2014 to 2021. Xizang was excluded because the published regional digital-economy series did not provide consistent coverage over the common study window. Agricultural variables were compiled from the National Bureau of Statistics of China and associated statistical yearbooks. Regional digital economy development (DED) followed the published provincial index of Chen *et al.* (2023). Digital-finance measures came from the Peking University Digital Financial Inclusion Index, including the overall index and usage-depth component (Guo *et al.* 2020). Urbanization rate and the natural logarithm of rural per-capita disposable income were used as controls.

CPSR was constructed from six plant-production indicators (Table 1). Major-crop yield was the combined production of rice, wheat and maize divided by their combined sown area. The effective irrigation-area ratio was effective irrigated area divided by total crop sown area; because these two official administrative aggregates use different land concepts, the ratio can exceed 1 in a small number of province-years and was not artificially capped. Mechanization intensity was agricultural machinery power per hectare of crop sown area. Crop diversity was the Simpson index, $1 - \sum s_i^2$, calculated from the sown-area shares of rice, wheat and maize. Fertilizer intensity was effective fertilizer component per hectare and entered CPSR in the negative direction. Disaster resistance was $1 - (\text{crop failure area} / \text{crop area affected by natural disasters})$; when the official table reported no affected crop area, resistance was coded as 1 and those cases were flagged during data quality control. Seven province-years with invalid crop-specific area or output placeholders (Hainan 2018-2021 and Qinghai 2019-2021) were treated as missing, giving 233 complete observations.

Table 1. Plant-production indicators used to construct crop production system resilience (CPSR) and descriptive statistics.

Indicator	Measurement / unit	Direction	Weight (%)	Mean $\pm$ SD	Range
Major-crop yield	Rice+wheat+maize output / sown area (t/ha)	+	13.13	6.12 $\pm$ 0.82	4.17-8.24
Irrigation area ratio	Effective irrigated area / crop sown area	+	29.57	0.449 $\pm$ 0.188	0.178-1.234
Mechanization intensity	Machinery power / crop sown area (kW/ha)	+	30.96	6.47 $\pm$ 2.29	3.18-13.87
Crop diversity	Simpson index, $1 - \sum s_i^2$	+	16.41	0.405 $\pm$ 0.178	0.000-0.634
Fertilizer intensity	Effective fertilizer component /crop sown area (kg/ha)	—	8.32	368.5 $\pm$ 138.4	140.1-799.6
Disaster resistance	$1 - \text{crop failure area} / \text{affected crop area}$	+	1.59	0.883 $\pm$ 0.077	0.312-1.000
CPSR	Weighted sum of six standardized indicators	—	100.00	0.4066 $\pm$ 0.1117	0.1992-0.7915

N: 233 complete province-year observations.

All six entropy weights were estimated on the same 233 complete observations. Let x_{ij} denote the observed value for province-year i and indicator j . Positive indicators (yield, irrigation-area ratio, mechanization, crop diversity and disaster resistance) were normalized using Eq. (1), whereas the negative indicator, fertilizer intensity, was normalized using Eq. (2).

$$z_{ij} = \frac{x_{ij} - \min(x_j)}{\max(x_j) - \min(x_j)} \quad (1)$$

$$z_{ij} = \frac{\max(x_j) - x_{ij}}{\max(x_j) - \min(x_j)} \quad (2)$$

For each indicator, the normalized share p_{ij} and entropy e_j were calculated using Eq. (3), followed by information utility d_j , entropy weight w_j and the final CPSR in Eq. (4). Here $n = 233$, and the conventional limit $0 \ln(0) = 0$ was used when $p_{ij} = 0$.

$$p_{ij} = \frac{z_{ij}}{\sum_i z_{ij}}, \quad e_j = -\frac{1}{\ln n} \sum_i p_{ij} \ln(p_{ij}) \quad (3)$$

$$d_j = 1 - e_j, \quad w_j = \frac{d_j}{\sum_j d_j}, \quad \text{CPSR}_i = \sum_j w_j z_{ij} \quad (4)$$

Thus, larger CPSR values indicate stronger crop-system resilience. The resulting weights are reported in Table 1. The primary panel model was:

$$\text{CPSR}_{it} = \alpha + \beta \text{DED}_{it} + \gamma' X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (5)$$

Where i indexes provinces and t indexes years; X_{it} contains urbanization rate and ln rural per-capita disposable income; μ_i and λ_t are province and year fixed effects, respectively; and ε_{it} is the error term. Standard errors were clustered by province. Robustness checks used equal CPSR weights, a five-indicator CPSR excluding disaster resistance, disaster exposure as an added control, the PKU overall digital-finance index, a balanced 28-province panel, one-year-lagged DED and a quadratic DED specification. The same fixed-effects design was applied separately to the six CPSR components, with Benjamini-Hochberg false-discovery-rate adjustment across the six component p-values.

For the plant-input analysis, fertilizer intensity (kg/ha) was the outcome and PKU digital-finance usage depth was standardized within each estimation sample. The baseline specification was:

$$\text{Fert}_{it} = \alpha + \theta \text{UsageDepth}_{it} + \gamma' X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (6)$$

Where θ measures the change in fertilizer intensity associated with a one-standard-deviation increase in digital-finance usage depth. The model retained the same province and year fixed effects and baseline controls. Sensitivity checks added major-crop yield or disaster exposure, used the balanced sample, lagged usage depth by one year, used a one-year lead placebo, winsorized the outcome, used a log-fertilizer specification and added province-specific linear trends. Small-cluster uncertainty was evaluated with province-clustered inference and wild-cluster bootstrap-t procedures; leave-one-province-out estimates assessed influence stability. A pesticide extension was examined only as supplementary confirmation because its sign and significance were sensitive to functional form.

Results and Discussion

The corrected CPSR averaged 0.4066 ± 0.1117 across 233 province-years (Table 1). Entropy weighting assigned the largest shares to mechanization (30.96%) and irrigation (29.57%), followed by crop diversity (16.41%), major-crop yield (13.13%), fertilizer intensity (8.32%) and disaster resistance (1.59%). These weights reflect the information dispersion of each standardized series rather than an assumption that infrastructure is biologically more important than shock response. The provincial maps showed marked spatial heterogeneity in CPSR, rice-wheat-maize

yield, crop diversity and fertilizer intensity (Fig. 1). The four patterns did not form a single common gradient, indicating that high crop productivity, structural diversity and low chemical-input pressure are distinct dimensions of crop-system performance. Provincial means for Hainan and Qinghai are based on the available valid crop-specific years.

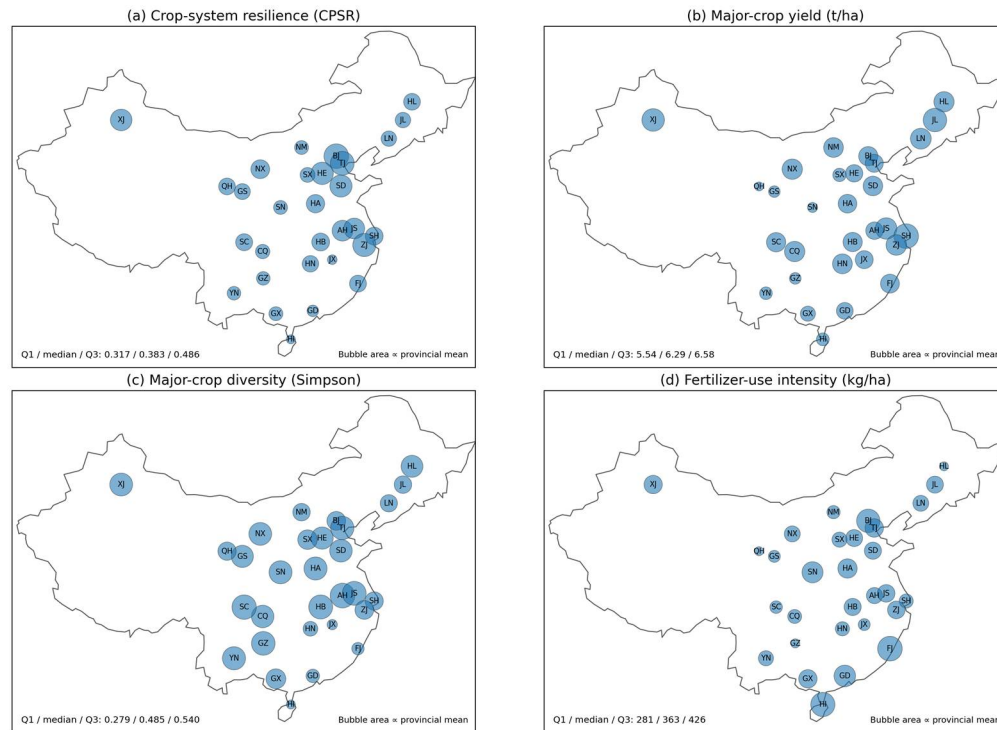


Fig. 1. Spatial organization of major-crop production systems across provincial China during 2014–2021. (a): Provincial mean crop production system resilience (CPSR). (b): Provincial mean rice-wheat-maize yield. (c): Provincial mean crop diversity measured by the Simpson index. (d): Provincial mean fertilizer-use intensity. Bubble area is proportional to the corresponding provincial mean, and points are positioned at provincial capitals. Xizang is not included because the regional digital-economy series was incomplete for the study period.

The balanced 28-province series further illustrates the difference between output growth and system-wide resilience (Fig. 2a–c). From 2014 to 2021, mean major-crop yield increased from 5.93 to 6.39 t/ha (7.8%), whereas CPSR increased from 0.4059 to 0.4179 (3.0%). Over the same period, mean fertilizer intensity declined from 390.2 to 327.0 kg/ha (16.2%). These descriptive trajectories suggest substantial improvement in output and chemical-input pressure without a comparably large rise in the broader resilience index, which also depends on relatively persistent irrigation, mechanization, crop-structure and shock-response conditions.

After province and year fixed effects were introduced, broad regional digital development did not show a detectable average association with CPSR. The core DED coefficient was -0.0150 (clustered SE = 0.0316, $p = 0.638$; Table 2). The conclusion remained unchanged with equal CPSR weights ($p = 0.152$), the five-indicator entropy index ($p = 0.697$), added disaster exposure ($p = 0.641$), the PKU overall digital-finance index ($p = 0.470$), the balanced sample ($p = 0.646$), one-year-lagged DED ($p = 0.500$) and a quadratic term ($p = 0.583$ for DED^2). The null estimate is therefore not explained by one weighting rule, the seven incomplete crop rows or a simple

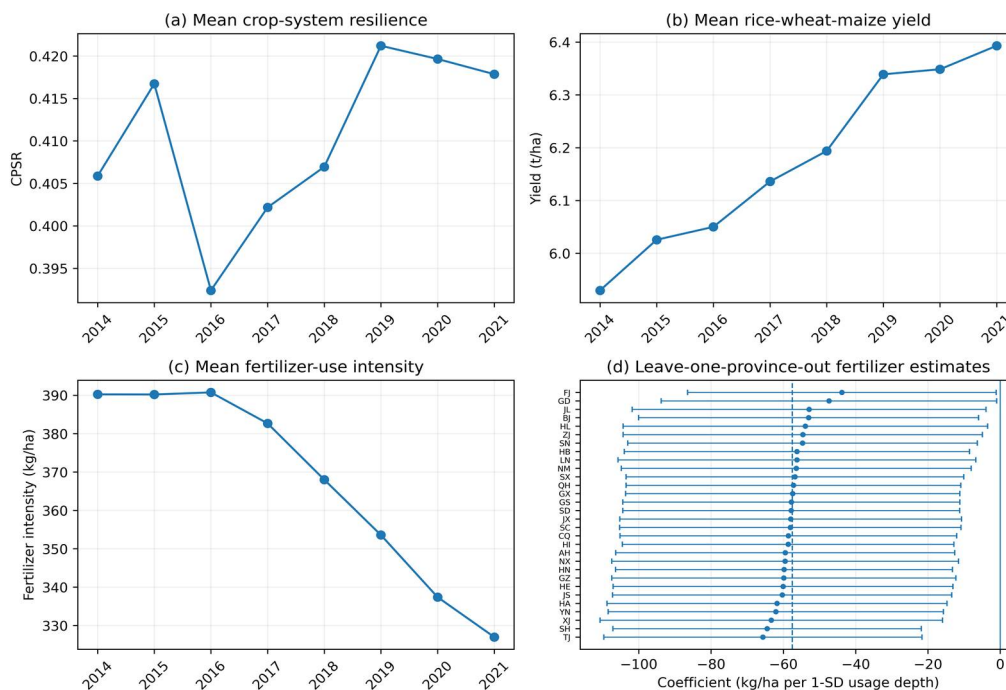


Fig. 2. Temporal crop-production patterns and fertilizer-association stability. Panels (a-c) show annual means in the balanced 28-province sample for CPSR, rice-wheat-maize yield and fertilizer intensity. Panel (d) shows leave-one-province-out estimates for the association between standardized digital-finance usage depth and fertilizer intensity; the dashed vertical line is the baseline coefficient.

nonlinear specification. It is also plausible biologically and agronomically because much of CPSR reflects infrastructure and crop-system structure that may not respond quickly to regional digital expansion.

Component models were consistent with this interpretation. The unadjusted DED association was negative for fertilizer intensity ($p = 0.064$) and for disaster resistance ($p = 0.015$), but neither remained significant after false-discovery-rate correction (adjusted $p = 0.193$ and 0.088 , respectively); yield, irrigation, mechanization and crop diversity were also non-significant (Table 2). Reporting the complete set of component tests is important because the overall CPSR result is null and isolated nominal p -values could otherwise be over-interpreted. The evidence therefore does not support a broad claim that regional digital development improved any single agronomic component during 2014-2021.

A more specific pattern emerged for fertilizer management when digital-finance usage depth, rather than the broad DED index, was examined. A one-standard-deviation increase in usage depth was associated with 57.5 kg/ha lower fertilizer intensity ($p = 0.0148$; Table 3), equivalent to 15.6% of the sample mean. The estimate was almost unchanged after controlling for major-crop yield or disaster exposure and in the balanced 28-province sample. One-year-lagged usage depth remained negative ($\beta = -70.49$ kg/ha, $p = 0.0055$), whereas the one-year lead placebo was not significant ($p = 0.168$). Wild-cluster bootstrap p -values were 0.0257 and 0.0231 under Rademacher and Webb weights, respectively, and every leave-one-province-out coefficient remained negative (Fig. 2d). These results make a single influential province or conventional clustered asymptotics an unlikely explanation for the baseline association.

Table 2. Association of regional digital economy development (DED) with CPSR and individual crop-system components.

Outcome	DED coefficient	Clustered SE	p	FDR-adjusted p	Result
CPSR	-0.0150	0.0316	0.638	—	Not significant
Major-crop yield	-0.2453	0.2336	0.302	0.605	Not significant
Irrigation-area ratio	0.0050	0.0401	0.902	0.902	Not significant
Mechanization intensity	-0.5259	0.8303	0.531	0.749	Not significant
Crop diversity	0.0143	0.0288	0.624	0.749	Not significant
Fertilizer intensity	-43.72	22.74	0.064	0.193	Not significant
Disaster resistance	-0.1064	0.0410	0.015	0.088	Not significant

Table 3. Digital-finance usage depth and fertilizer-use intensity.

Specification	N	Coefficient	Clustered SE	p	Interpretation
Baseline two-way FE	233	-57.52	23.60	0.0148	Lower fertilizer intensity
+ major-crop yield	233	-57.30	23.53	0.0149	Estimate unchanged
+ disaster exposure	233	-57.44	23.84	0.0160	Estimate unchanged
Balanced 28 provinces	224	-58.38	23.41	0.0126	Sample robustness
Usage depth lagged one year	203	-70.49	25.40	0.0055	Temporal ordering check
Usage depth lead one year	203	-26.30	19.06	0.1676	Placebo not significant
Province-specific linear trends	233	-13.97	16.30	0.3914	Trend sensitivity

Fertilizer intensity is kg/ha; standardized PKU usage-depth coefficients are therefore kg/ha per 1-SD increase. Level models include province and year fixed effects plus baseline controls unless stated. Wild-cluster bootstrap p-values were 0.0257 (Rademacher) and 0.0231 (Webb); the leave-one-province-out estimates remained negative (Fig. 2d).

The fertilizer evidence nevertheless has clear limits. When province-specific linear trends were added, the coefficient fell to -13.97 kg/ha and became imprecise ($p = 0.391$), and the log-fertilizer specification was also non-significant ($p = 0.157$). Moreover, the available data did not show a detectable effect on major-crop yield or a simple yield-to-fertilizer proxy. The result should therefore be interpreted as lower fertilizer-use intensity, not improved fertilizer-use efficiency. This distinction is consistent with farmer-level evidence that digital capabilities may alter fertilizer decisions through information, service access and management channels (Liu *et al.* 2026), while field studies show that agronomic efficiency ultimately depends on the timing, source and crop response to nutrients (Kumar and Swain 2025, Sujatha *et al.* 2025).

Taken together, the study shows that provincial rice-wheat-maize systems cannot be characterized by yield alone: productive performance, water and mechanical capacity, crop diversity, chemical-input pressure and disaster loss contribute differently to resilience. Broad digital economy development was not associated with a measurable short-run increase in composite crop-system resilience, whereas deeper use of digital financial services was consistently associated with lower fertilizer intensity under the main fixed-effects design. For crop production, the practical implication is not that digital expansion automatically creates resilience, but that digital services may be most useful when linked to crop-specific nutrient management, agronomic information and resource-management institutions.

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