

SPATIOTEMPORAL DYNAMICS AND DRIVING FORCES OF GREEN TRANSITION OF CULTIVATED LAND IN HENAN PROVINCE, CHINA

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Abstract

Henan Province, China's second-largest grain-producing region accounting for approximately 10% of national output, has pursued green agricultural transformation to balance food security with environmental sustainability. However, systematic prefecture-level evaluations remain limited. This study evaluates the Green Transition of Cultivated Land (GTCL) across 18 prefectures using panel data from 2000, 2010, and 2020. The GTCL index integrates Spatial Transition and Mode Transition. The provincial GTCL index increased from 0.41 to 0.52 (+27%), with substantial spatial heterogeneity. Hebi achieved the highest GTCL (0.68), followed by Jiaozuo (0.64), while Sanmenxia recorded the lowest (0.41). Four north-central prefectures emerged as green leaders with GTCL above 0.55. Critically, fertilizer intensity increased in all prefectures from 467 to 592 kg/ha (+26.8%), contrasting with national "zero growth" claims. Pesticide intensity decreased in 11 prefectures from 11.2 to 10.6 kg/ha (-5.4%). Grain yield increased from 4.86 to 6.27 t/ha (+29%). Water-saving irrigation correlated strongly with GTCL ($r = 0.62$) and yield ($r = 0.63$). Prefectures were classified into five types: green leaders, intensive conventional, degrading, low-input lagging, and mixed or stable. Differentiated policy recommendations include input reduction for intensive conventional prefectures, productivity enhancement for low-input lagging prefectures, and knowledge transfer from green leaders.

Introduction

China's agricultural sector has achieved remarkable growth in grain production over the past four decades, largely driven by intensive use of chemical fertilizers, pesticides, plastic film, and irrigation (Zhao *et al.* 2008, Zhang *et al.* 2021). However, this high-input model has generated significant environmental costs, including soil acidification, water pollution, greenhouse gas emissions, and biodiversity loss (Jiao *et al.* 2016). Henan Province, located in the Yellow River Basin, is China's second-largest grain-producing region, accounting for approximately 10% of national grain output (Yang *et al.* 2025). The province's agricultural systems are dominated by wheat-maize double cropping in the eastern plains and wheat-rice systems in the southern region. Intensive farming has led to soil degradation, groundwater depletion, and high fertilizer application rates (Gao *et al.* 2024). Since 2015, the Chinese government has promoted green agricultural transformation as a national priority, emphasizing reduced chemical inputs, improved efficiency, and ecological restoration (Xin 2022). Henan has implemented various green agriculture policies, including soil testing and formula fertilization, manure nutrient utilization, conservation tillage, and water-saving irrigation (Yang *et al.* 2025).

The Green Transition of Cultivated Land (GTCL) framework evaluates agricultural transformation across three interconnected subsystems: Spatial Transition, Functional Transition, and Mode Transition (Lu *et al.* 2020, Niu *et al.* 2022). Spatial Transition captures the physical

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reorganization of cropland and infrastructure through indicators including irrigation coverage, water-saving irrigation share, and machinery density. Functional Transition captures changes in input intensity and efficiency through fertilizer intensity, pesticide intensity, and fertilizer efficiency. Mode Transition captures changes in production outcomes through grain yield and yield stability. Following Niu *et al.* (2022), weights are assigned as 0.35 for Spatial Transition, 0.40 for Functional Transition, and 0.25 for Mode Transition. Unlike single-indicator assessments, GTCL provides a composite measure suitable for spatial comparison and policy targeting.

Despite policy emphasis on green agriculture, systematic evaluations at the prefecture level remain limited. Most existing studies focus on national or provincial aggregates, obscuring spatial heterogeneity and local dynamics (Xie *et al.* 2023, Yang *et al.* 2025). Furthermore, few studies simultaneously examine multiple dimensions of transformation including chemical inputs, yield outcomes, irrigation efficiency, and machinery use within an integrated framework. This study addresses these gaps by pursuing the following aims and objectives.

The overall aim of this study is to evaluate the green agricultural transformation and its effects on cropland ecology and grain production in Henan Province from 2000 to 2020 using the GTCL framework. The specific objectives are as follows: to compute the GTCL index and its three subsystem scores for all 18 prefectures in Henan for the years 2000, 2010, and 2020; to analyze the temporal trends and spatial heterogeneity of green transformation across the province; to quantify changes in chemical input intensities including fertilizer, pesticide, and plastic film, as well as grain yield and fertilizer efficiency over the two-decade period; to classify prefectures into a green transformation typology based on their fertilizer intensity and yield changes; to identify the key drivers of green transition through correlation analysis between GTCL components, irrigation indicators, and yield outcomes; and to propose differentiated policy recommendations for land use planning and agricultural management tailored to each prefecture type.

Materials and Methods

Henan Province is located in central-eastern China between 31°23' and 36°22' N latitude and 110°21' and 116°39' E longitude, covering 167,000 km² (Fig. 1). The province has a warm temperate continental monsoon climate with mean annual temperature of 13–15°C and annual precipitation of 500–900 mm, decreasing from south to north (Song and Kim 2025). Henan comprises 17 prefecture-level cities and one county-level city (Jiyuan), treated as a prefecture-level unit for analysis, resulting in 18 observational units. Agricultural systems vary significantly by region. The eastern plain prefectures (Kaifeng, Shangqiu, Zhoukou, Zhumadian, Puyang, Hebi, Anyang, Xinxiang, Jiaozuo, Xuchang, Luohe) practice wheat-maize double cropping with high irrigation coverage. The western mountain prefectures (Luoyang, Sanmenxia, Pingdingshan) practice wheat-corn rotation with lower yields and fragmented land. The southern prefectures (Nanyang, Xinyang) practice wheat-rice systems with higher precipitation and lower irrigation dependence.

Data were extracted from the Henan Statistical Yearbooks for 2001, 2011, and 2021, reporting statistics for 2000, 2010, and 2020 respectively (National Bureau of Statistics of China, 2022). The dataset includes 18 prefecture-level units at three time points, yielding 54 observations. Variables include grain output (10,000 tons), grain sown area (1,000 ha), fertilizer use (tons, 100% effective component), pesticide use (tons), plastic film use (tons), irrigated area (1,000 ha), water-saving irrigated area (1,000 ha), and agricultural machinery power (10,000 kW).

For each prefecture i and year t , we calculated raw indicators. Grain yield (t/ha) was calculated as:

$$Y_{it} = (G_{it} \times 10) / A_{it}$$

where Y is yield, G is grain output, and A is grain sown area. The multiplier 10 converts units consistently.

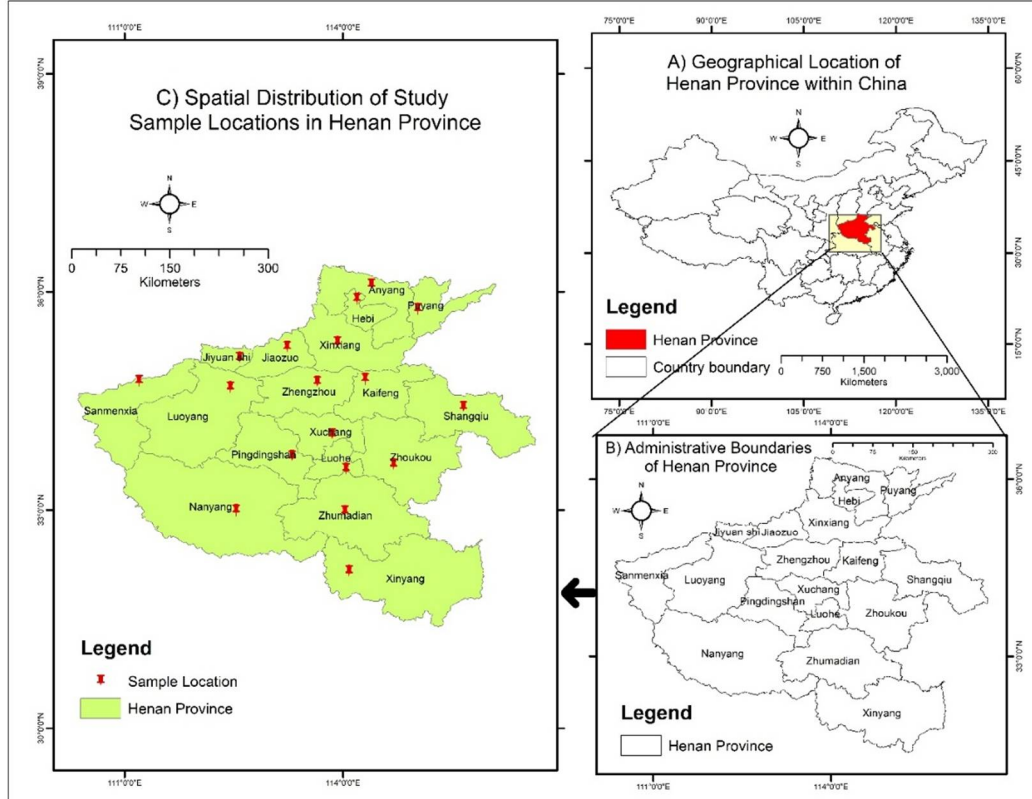


Fig. 1. Spatial distribution of study sample locations in Henan Province, China.

Fertilizer intensity (kg/ha) was calculated as:

$$F_{it} = (FERT_{it} \times 1000) / A_{it}$$

where F is fertilizer intensity and FERT is fertilizer use. Pesticide intensity (P) and plastic film intensity (PF) were calculated similarly.

Machinery density (kW/ha) was calculated as:

$$M_{it} = (MP_{it} \times 10) / A_{it}$$

where M is machinery density and MP is agricultural machinery power.

Irrigation coverage (%) was calculated as:

$$I_{it} = (IRR_{it} / A_{it}) \times 100$$

where I is irrigation coverage and IRR is irrigated area.

Water-saving irrigation share (%) was calculated as:

$$WS_{it} = (WSIRR_{it} / IRR_{it}) \times 100$$

where WS is water-saving irrigation share and WSIRR is water-saving irrigated area. This indicator was available only for 2020; for 2000 and 2010, we set it to zero as a baseline.

Fertilizer efficiency (kg grain/kg fertilizer) was calculated as:

$$E_{it} = (Y_{it} \times 1000) / F_{it}$$

where E is fertilizer efficiency.

Yield stability was calculated as the relative change from 2000 to 2020:

$$S_i = (Y_{i,2020} - Y_{i,2000}) / Y_{i,2000}$$

The GTCL index was constructed following Niu *et al.* (2022) and Tang and Chen (2020) across three subsystems. Spatial Transition (ST) includes irrigation coverage, water-saving irrigation share, and machinery density. Functional Transition (FT) includes fertilizer intensity (inverse), pesticide intensity (inverse), and fertilizer efficiency. Mode Transition (MT) includes grain yield and yield stability. Weights are 0.35 for ST, 0.40 for FT, and 0.25 for MT following Tang and Chen (2020).

Before combining indicators, we normalized each to a 0-1 scale using min-max normalization separately for each year. For positive indicators (higher = greener: irrigation, water-saving irrigation, machinery, yield, fertilizer efficiency, yield stability):

$$X_{it}^{norm} = (X_{it} - X_t^{min}) / (X_t^{max} - X_t^{min})$$

For negative indicators (lower = greener: fertilizer intensity, pesticide intensity):

$$X_{it}^{norm} = (X_t^{max} - X_{it}) / (X_t^{max} - X_t^{min})$$

Subsystem scores were calculated as arithmetic means:

$$ST_{it} = (I_{it}^{norm} + WS_{it}^{norm} + M_{it}^{norm}) / 3$$

$$FT_{it} = (F_{it}^{norm} + P_{it}^{norm} + E_{it}^{norm}) / 3$$

$$MT_{it} = (Y_{it}^{norm} + S_i^{norm}) / 2$$

The GTCL index was calculated as the weighted sum:

$$GTCL_{it} = 0.35 \times ST_{it} + 0.40 \times FT_{it} + 0.25 \times MT_{it}$$

Absolute and percentage changes were calculated for 2000–2010, 2010–2020, and 2000–2020:

$$\Delta_{2000-2010} = X_{i,2010} - X_{i,2000}$$

$$\Delta \%_{2000-2010} = \left((X_{i,2010} - X_{i,2000}) / X_{i,2000} \right) \times 100$$

Prefectures were classified into five types based on fertilizer and yield changes (2000–2020). Green leaders: fertilizer increase <15% and yield increase >20%. Intensive conventional: both increases >20%. Degrading: fertilizer increase >20% but yield increase <30%. Low-input lagging: fertilizer increase <15% and yield increase <20%. Mixed/stable: fertilizer increase 15-20% and yield increase 20–30%.

Descriptive statistics (mean, standard deviation, min, max) were computed for all indicators by year. Pearson correlation coefficients were calculated between GTCL components, input intensities, yield, and irrigation indicators. Choropleth maps were created to visualize spatial patterns of GTCL, input intensity changes, and typology using prefecture boundary shapefiles from the Resources and Environmental Sciences Data Center of the Chinese Academy of Sciences. All calculations were performed using Microsoft Excel 2019.

Results and Discussion

The Green Transition of Cultivated Land (GTCL) index increased province-wide from 0.41 in 2000 to 0.52 in 2020, representing a 27% increase over two decades (Fig. 2). The GTCL index in 2010 was 0.48, indicating that most improvement occurred between 2000 and 2010, with slower

progress in the second decade. This suggests that early investments in agricultural infrastructure and input efficiency yielded rapid returns, while recent gains have faced diminishing returns.

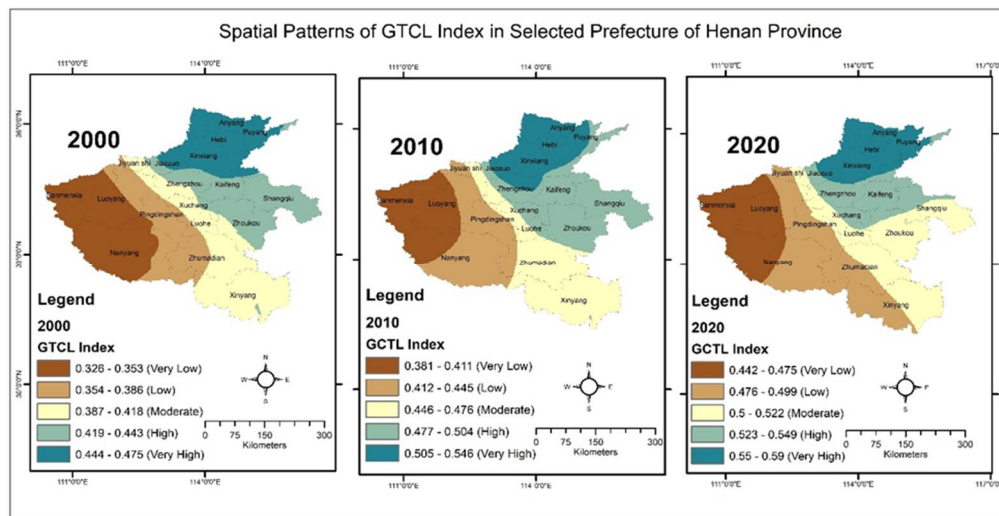


Fig. 2. Green Transition of Cultivated Land (GTCL) index for 18 prefectures in Henan Province, 2000. Higher scores indicate greater progress toward green agricultural transformation.

Substantial spatial heterogeneity exists across Henan's prefectures. In 2020, Hebi achieved the highest GTCL score of 0.68, followed by Jiaozuo (0.64), Xuchang (0.58), and Puyang (0.57). Sanmenxia recorded the lowest score of 0.41, followed by Pingdingshan (0.44) and Jiyuan (0.47). North-central prefectures form a green transition cluster with scores above 0.55, while western prefectures lag below 0.48. Eastern plain prefectures show medium scores between 0.50 and 0.53. This spatial divide reflects differences in physical geography, infrastructure, and policy history. Eastern prefectures have deep alluvial soils, flat terrain, and access to Yellow River irrigation, while western mountain prefectures have thin soils, fragmented land, and limited irrigation access (Qu *et al.* 2022, Xi *et al.* 2022).

The largest GTCL increase occurred in Hebi (0.20), followed by Zhengzhou (0.17) and Nanyang (0.15). The smallest increases were in Xinxiang (0.05), Jiyuan (0.06), and Zhoukou and Shangqiu (0.07 each). Hebi's emergence as the top performer demonstrates that rapid green transition is achievable with appropriate policies. Its success stems from early adoption of water-saving irrigation (79% coverage) and integrated pest management, which reduced pesticide intensity by 45.8%, the province's largest reduction.

Examining the three subsystems reveals that both Spatial Transition and Functional Transition improved by 0.12 points, while Mode Transition improved by only 0.08 points (Table 1). This indicates that infrastructure development and input efficiency have outpaced yield gains as drivers of green transition. The smaller Mode Transition improvement is expected because grain yields were already relatively high in 2000 (4.86 t/ha), leaving less room for dramatic increases.

Hebi achieved the highest ST score in 2020 (0.71), followed by Jiaozuo (0.66) and Zhengzhou (0.62). The largest ST increases occurred in Hebi (0.29), Zhengzhou (0.27), and Xuchang (0.20), reflecting investments in irrigation infrastructure and mechanization (Fig. 3). Hebi also achieved the highest FT score (0.68), followed by Jiaozuo (0.63) and Puyang (0.57). Hebi's high FT score reflects its lowest provincial fertilizer intensity (410 kg/ha), lowest pesticide intensity (5.25 kg/ha),

and highest fertilizer efficiency (18.18 kg grain per kg fertilizer). For Mode Transition, Luohe achieved the highest MT score (0.54), with large increases in yield gains from low baselines. Zhumadian increased yield from 3.70 to 6.25 t/ha (69%), while Luohe increased from 4.36 to 6.99 t/ha (60%). This convergence pattern aligns with technology diffusion theories (Foster and Rosenzweig 2010).

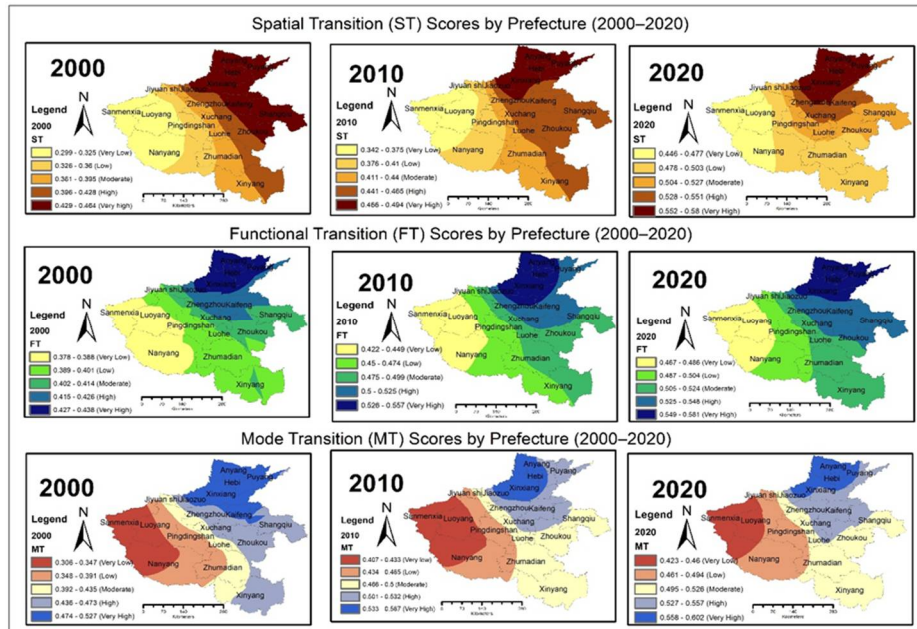


Fig. 3. Spatial Transition (ST), Functional Transition (FT), and Mode Transition (MT) scores for 18 prefectures in Henan Province, 2000, 2010, and 2020.

Table 1. Provincial average subsystem scores, Henan Province, 2000–2020.

Subsystem	2000	2010	2020	Change 2000–2020
Spatial Transition (ST)	0.40	0.44	0.52	+0.12
Functional Transition (FT)	0.41	0.50	0.53	+0.12
Mode Transition (MT)	0.44	0.50	0.52	+0.08

Fertilizer intensity increased in all 18 prefectures from 2000 to 2020, with the provincial average rising from 467 to 592 kg/ha (26.8% increase) (Table 2). This finding that no prefecture reduced fertilizer intensity is the most concerning result, contrasting sharply with national "zero growth" claims (Cui *et al.* 2023). The smallest increases occurred in Xuchang (4.2%), Jiaozuo (5.6%), and Nanyang (6.9%). The largest increases occurred in Luohe (58.9%), Xinxiang (47.8%), Pingdingshan (46.9%), and Xinyang and Luoyang (approximately 41% each). Several explanations are plausible. China's fertilizer use peaked nationally around 2015 (Ji *et al.* 2020), but Henan may lag due to yield pressure from its strategic food security role. Additionally, high-yield crop varieties may increase nutrient demand, leading farmers to apply more fertilizer to maximize yields. Henan requires accelerated fertilizer reduction policies, prioritizing Luohe, Xinxiang, Pingdingshan, Luoyang, Xinyang, and Shangqiu. The success of Xuchang and Jiaozuo demonstrates that near-zero growth is achievable.

Table 2 Changes in fertilizer intensity (kg/ha), pesticide intensity (t/ha) and grain yield (t/ha) across 18 prefectures in Henan Province, 2000–2020.

Prefecture	Fertilizer intensity			Pesticide intensity			Grain Yield					
	2000	2010	2020	Change (%)	2000	2010	2020	Change (%)	2000	2010	2020	Change (%)
Zhengzhou	503	412	623	+23.9	8.5	8.2	9.3	+9.4	3.96	7.87	5.07	+28.0
Kaifeng	485	425	603	+24.3	13.2	9.4	8.1	-38.6	5.01	8.95	5.94	+18.6
Luoyang	326	485	459	+40.8	5.6	8.1	7.7	+37.5	3.93	7.88	5.07	+29.0
Pingdingshan	516	615	758	+46.9	5.1	8.0	7.3	+43.1	3.51	8.36	5.27	+50.1
Anyang	516	543	716	+38.8	12.0	9.6	9.3	-22.5	5.04	8.06	6.85	+35.9
Hebi	352	342	410	+16.5	9.6	7.2	5.2	-45.8	5.36	8.72	7.45	+39.0
Xinxiang	481	510	711	+47.8	10.6	12.9	11.1	+4.7	5.65	8.69	6.76	+19.6
Jiaozuo	640	540	676	+5.6	13.2	12.3	12.6	-4.5	7.34	8.53	7.59	+3.4
Puyang	551	514	665	+20.7	10.6	9.5	7.3	-31.1	5.70	8.38	6.97	+22.3
Xuchang	428	585	446	+4.2	6.7	10.2	6.8	+1.5	5.94	8.11	6.76	+13.8
Luohe	397	482	631	+58.9	8.4	6.9	8.0	-4.8	4.36	9.33	6.99	+60.3
Sanmenxia	452	550	502	+11.1	10.1	15.7	14.2	+40.6	3.00	8.41	4.52	+50.7
Nanyang	534	517	571	+6.9	14.2	13.5	10.6	-25.4	3.81	9.17	5.53	+45.1
Shangqiu	454	493	639	+40.7	13.3	12.8	8.6	-35.3	5.12	9.24	6.79	+32.6
Xinyang	386	570	544	+40.9	8.5	10.1	12.3	+44.7	5.17	9.06	6.91	+33.7
Zhoushou	520	522	628	+20.8	20.2	14.5	13.6	-32.7	5.31	9.41	6.80	+28.1
Zhumadian	498	434	560	+12.4	4.7	3.7	5.7	+21.3	3.70	9.48	6.25	+68.9
Jiyuan	462	385	553	+19.7	9.7	9.2	10.5	+8.2	4.93	8.14	5.67	+15.0
Provincial average	467	493	592	+26.8	11.2	10.9	10.6	-5.4	4.86	8.68	6.27	+29.0

Unlike fertilizer, pesticide intensity decreased in 11 of 18 prefectures, with the provincial average declining from 11.2 to 10.6 kg/ha (5.4% decrease) (Table 2). The largest decreases occurred in Hebi (45.8%), Kaifeng (38.6%), Shangqiu (35.3%), and Zhoukou (32.7%). In contrast, the largest increases occurred in Xinyang (44.7%), Pingdingshan (43.1%), Sanmenxia (40.6%), and Luoyang (37.5%). Eastern plain prefectures with larger fields and better extension services have successfully reduced pesticide use, while western mountain prefectures with fragmented land and smallholder dominance have increased use. This aligns with Wang *et al.* (2020) and Xin (2022). Targeted pesticide reduction programs are needed for western and southern prefectures. Hebi's success in reducing pesticide intensity by nearly half while increasing yield by 39% demonstrates that large reductions are possible without compromising productivity.

Grain yield increased in all prefectures, with the provincial average rising from 4.86 to 6.27 t/ha (29% increase) (Table 2). The largest yield increases occurred in Zhumadian (68.9%), Luohe (60.3%), Sanmenxia (50.7%), and Pingdingshan (50.1%). The smallest increases were in Jiaozuo (3.4%), Xuchang (13.8%), and Jiyuan (15.0%). The highest 2020 yields were in Jiaozuo (7.59 t/ha), Hebi (7.45 t/ha), and Luohe (6.99 t/ha). The lowest were in Sanmenxia (4.52 t/ha), Zhengzhou (5.07 t/ha), and Luoyang (5.07 t/ha). The convergence pattern, where lower-yielding prefectures experienced larger percentage increases, is consistent with technology diffusion models. However, the persistent yield gap of more than 3 t/ha between highest and lowest prefectures indicates significant productivity gains remain possible.

Table 3 Green transformation typology of Henan prefectures (2000–2020).

Type	Prefectures	Number	Average fertilizer change (%)	Average yield change (%)	Average GTCL 2020
Green leader	Hebi, Jiaozuo, Zhengzhou, Xuchang	4	+12.5	+21.1	0.61
Intensive conventional	Kaifeng, Anyang, Xinxiang, Puyang, Shangqiu, Zhoukou	6	+33.8	+25.3	0.53
Degrading	Luoyang, Pingdingshan	2	+43.9	+39.6	0.46
Low-input lagging	Sanmenxia, Nanyang, Jiyuan	3	+12.6	+36.9	0.46
Mixed/stable	Luohe, Zhumadian, Xinyang	3	+37.4	+54.3	0.50

Based on changes in fertilizer intensity and grain yield, we classified the 18 prefectures into five types (Table 3). The four green leaders (Hebi, Jiaozuo, Zhengzhou, Xuchang) achieved the smallest fertilizer increases (12.5% average) while maintaining strong yield growth (21.1% average). They have the highest average GTCL score of 0.61, demonstrating that high yield and green practices are compatible. Hebi's balanced performance across all three subsystems makes it a model for emulation. The six intensive conventional prefectures, primarily in the eastern plain, increased both fertilizer and yield substantially (33.8% and 25.3%, respectively). Their average GTCL score of 0.53 is moderate. They should implement soil testing with compliance monitoring, establish pesticide reduction targets of at least 20% by 2030, expand water-saving irrigation from the current 32% average to over 60%, and implement plastic film recycling.

The three low-input lagging prefectures (Sanmenxia, Nanyang, Jiyuan) had the smallest fertilizer increases (12.6%) but also the lowest yields, with Sanmenxia at only 4.52 t/ha. This productivity gap requires land consolidation, drought-tolerant variety development, subsidized small-scale irrigation, and off-farm income support. The two degrading prefectures (Luoyang, Pingdingshan) showed high fertilizer increases (43.9%) with yield increases of 39.6%, suggesting diminishing returns. They require extension services focused on best management practices and soil health restoration. The three mixed prefectures (Luohe, Zhumadian, Xinyang) showed high yield increases (54.3%) but also high fertilizer increases (37.4%). They need targeted support:

Luohe needs water-saving irrigation expansion (currently only 19%), Xinyang needs pesticide reduction to reverse its 44.7% increase, and Zhumadian needs moderate fertilizer reduction.

The Pearson correlation matrix shows GTCL positively correlated with grain yield ($r = 0.58$, $p < 0.01$) and water-saving irrigation share ($r = 0.62$, $p < 0.01$) (Fig. 4). Grain yield is also positively correlated with water-saving irrigation share ($r = 0.63$, $p < 0.01$). Prefectures with high water-saving irrigation shares (Hebi 79%, Jiaozuo 78%, Xuchang 78%, Puyang 69%) achieved the highest GTCL scores with below-average fertilizer intensity. This aligns with evidence that drip irrigation can reduce fertilizer requirements by 20-30% while maintaining yields (Qin *et al.* 2024, Wu *et al.* 2025). Fertilizer intensity shows weak correlations with yield ($r = 0.31$) and pesticide intensity ($r = 0.35$), suggesting diminishing returns. Pesticide intensity shows no significant correlation with yield ($r = 0.15$) or GTCL ($r = -0.08$), indicating it can be reduced without compromising productivity. Prefectures with low water-saving irrigation shares (Luohe 19%, Kaifeng 20%, Xinyang 20%, Shangqiu 28%, Zhoukou 29%) face a double challenge of higher water use and lower fertilizer efficiency. Expanding water-saving irrigation should be a policy priority.

Although not included in the GTCL index, plastic film intensity increased dramatically by 240% province-wide from 2000 to 2020, with largest increases in Anyang (1,215%), Hebi (600%), and Puyang (515%). Plastic film residue is an emerging threat, with studies documenting microplastic accumulation and soil degradation (Li *et al.* 2022, Wang *et al.* 2024). Henan should establish recycling programs with deposit-refund systems, promote biodegradable alternatives, and monitor soil microplastic levels in high-use prefectures.

Several limitations should be acknowledged. Direct ecological measurements were not obtained; chemical input intensity served as a proxy. Only three time points were analyzed, missing annual variability. The analysis is descriptive and correlational; causal policy effects were not modeled. Economic outcomes and farmer behavior data were unavailable. Future research should integrate field sampling, high-frequency data, causal designs, and farmer surveys.

In conclusion, Henan's green agricultural transformation progressed by 27% from 2000 to 2020, but fertilizer intensity increased in all prefectures while pesticide reduction succeeded only in the east. Four green leaders (Hebi, Jiaozuo, Zhengzhou, Xuchang) demonstrated that high yield and green practices are compatible. Differentiated policies are required for each prefecture type, with water-saving irrigation identified as a key leverage point for sustainable intensification.

References

- Cui M, Guo Q, Wei Y, Yu X, Hu J, Tian L and Kong J 2023. Variations and its driven factors of anthropogenic nitrogen loads in the Yangtze River Economic Belt during 2000–2019. *Environ. Sci. Pollut. Res.* **30**(2): 2450-2468.
- Foster AD and Rosenzweig MR 2010. Microeconomics of technology adoption. *Annu. Rev. Econ.* **2**(1): 395-424.
- Gao L, Wu Y, Li L, Sun C, Li D and Liu X 2024. A risk assessment method for phosphorus loss in intensive agricultural areas—a case study in Henan Province, China. *Agriculture* **14**(10): 1681.
- Ji Y, Liu H and Shi Y 2020. Will China's fertilizer use continue to decline? Evidence from LMDI analysis based on crops, regions and fertilizer types. *PLoS ONE* **15**(8): e0237234.
- Jiao X, Lyu Y, Wu X, Li H, Cheng L, Zhang C, Yuan L, Jiang R, Jiang B, Rengel Z and Zhang F 2016. Grain production versus resource and environmental costs: towards increasing sustainability of nutrient use in China. *J. Exp. Bot.* **67**(17): 4935-4949.
- Li S, Ding F, Flury M, Wang Z, Xu L, Li S, Jones DL and Wang J 2022. Macro- and microplastic accumulation in soil after 32 years of plastic film mulching. *Environ. Pollut.* **300**: 118945.

- Lu X, Qu Y, Sun P, Yu W and Peng W 2020. Green transition of cultivated land use in the Yellow River Basin: A perspective of green utilization efficiency evaluation. *Land* **9**(12): 475.
- National Bureau of Statistics of China 2022. Annual Statistical Data on Agricultural Production in China. China Statistics Press, Beijing.
- Niu S, Lyu X and Gu G 2022. A new framework of green transition of cultivated land-use for the coordination among the water-land-food-carbon nexus in China. *Land* **11**(6): 933.
- Qin J, Fan X, Wang X, Jiang M and Lv M 2024. The effects of irrigation and nitrogen application on the water and nitrogen utilization characteristics of drip-irrigated winter wheat in the North China Plain. *Agronomy* **14**(11): 2629.
- Qu L, Li Y, Chen Z and Huang Y 2022. Exploring the spatiotemporal variation characteristics and influencing factors of gully agricultural production transformation in the Chinese Loess Plateau: A case study of loess hilly and gully region in Yan'an City. *Land Use Policy* **123**: 106369.
- Song M and Kim JE 2025. Spatial distribution characteristics and driving factors of traditional villages in Henan Province: A multi-method comprehensive analysis. *Sustainability* **17**(23): 10825.
- Tang Y and Chen M 2022. The impact mechanism and spillover effect of digital rural construction on the efficiency of green transformation for cultivated land use in China. *Int. J. Environ. Res. Public Health* **19**: 16159.
- Wang C, Li S, Huang S and Feng X 2024. A review of the application and impact of drip irrigation under plastic mulch in agricultural ecosystems. *Agronomy* **14**(8): 1752.
- Wang J, Wei H, Cheng K, Ochir A, Davaasuren D, Li P, Chan FKS and Nasanbat E 2020. Spatio-temporal pattern of land degradation from 1990 to 2015 in Mongolia. *Environ. Dev.* **34**: 100497.
- Wu X, Huang Z, Huang C, Liu Z, Liu J, Cao H and Gao Y 2025. Regulated deficit irrigation improves yield formation and water and nitrogen use efficiency of winter wheat at different soil fertility levels. *Agronomy* **15**(8): 1874.
- Xi X, Wang YW and Qiao JJ 2022. Spatial distribution characteristics and influencing factors of specialized villages in Henan Province. *Front. Bus. Econ. Manage.* **5**(1): 10-14.
- Xie Y, Zhu Q, Bai H, Luo P and Liu J 2023. Spatio-temporal evolution and coupled coordination of LUCC and ESV in cities of the Transition Zone, Shenmu City, China. *Remote Sensing* **15**(12): 3136.
- Xin L 2022. Chemical fertilizer rate, use efficiency and reduction of cereal crops in China, 1998–2018. *J. Geogr. Sci.* **32**(1): 65-78.
- Yang J, Cai E, Chen W, Li L, Jing Y and Li Y 2025. Quantitative evaluation and driving forces of green transition of cultivated land use in major grain-producing areas—A case study of Henan Province, China. *Sustainability* **17**(6): 2624.
- Zhang QQ, Ma ZR, Cai YY, Li HR and Ying GG 2021. Agricultural plastic pollution in China: Generation of plastic debris and emission of phthalic acid esters from agricultural films. *Environ. Sci. Technol.* **55**(18): 12459-12470.
- Zhao J, Luo Q, Deng H and Yan Y 2008. Opportunities and challenges of sustainable agricultural development in China. *Phil. Trans. R. Soc. B* **363**(1492): 893-904.

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