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Chenyan Lin
Fujian Agricultural and Forestry University
Zhen Xie
zxie7003@fafu.edu.cn

Fujian Agricultural and Forestry University
Quan Zhou
Fujian Agricultural and Forestry University

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Cultivated Land System Resilience Responses and Efficiency Synergy Mechanisms under Dietary-Transition Pressure in China

Chenyan Lin [1, 2], Zhen Xie [1, 2✉], Quan Zhou [1, 2]

[1] College of Public Administration & Law, Fujian Agricultural and Forestry University, Fuzhou, 350002, China.

[2] Technology Innovation Center for Monitoring and Restoration Engineering of Ecological Fragile Zone in Southeast China, Ministry of Natural Resource, Fuzhou, 350001, China.

✉ Corresponding author

Correspondence to: zxie7003@fafu.edu.cn

Abstract

The ongoing shift in dietary consumption among Chinese residents from staple grain-based diets toward more diversified and nutritious dietary patterns is reshaping resource demand, production organization, and regional supply–demand relationships within cultivated land systems. Against this backdrop, cultivated land systems must not only maintain their grain production capacity but also remain resilient to resource constraints, ecological risks, and regional supply–demand mismatches. To address these challenges, this study develops an integrated framework for evaluating dietary transition pressure, cultivated land system resilience, and cultivated land green use efficiency across 30 provincial-level administrative units in mainland China. First, we identify the spatiotemporal variations in cropping structures and cropping patterns across China. Second, the resilience of the cultivated land system is assessed along three dimensions: resistance, stability, and adaptability. Third, we examine the dynamic responses of multidimensional resilience to pressure from dietary transition. Finally, we evaluate the synergistic sustainability of cultivated land green use efficiency and multidimensional resilience. The results show that China's cultivated land demand pressure increased from 0.93 to 1.45 between 2000 and 2024, while the number of provinces with a pressure index exceeding 1 rose from 10 to 13, indicating that dietary transitions have placed increasing pressure on cultivated land resources. Cultivated land system resilience exhibits a pronounced north–south differentiation, with northern China demonstrating increasingly strong stability advantages supported by concentrated staple grain production and stable cropping systems, whereas southern China shows more substantial improvements in adaptability alongside the diversification of cropping structures. Further analysis reveals distinct resilience response pathways between northern and southern China. In southern China, increasing demand pressure suppresses stability and resistance in the short term, while adaptability remains highly persistent. In contrast, northern China responds to changes in demand primarily through short-term adjustments and subsequent recovery in stability. Meanwhile, cultivated land green use efficiency has improved overall, but its coordination with resistance has improved only marginally, suggesting that efficiency gains and enhanced resistance have yet to progress in tandem. The proposed analytical framework and empirical findings provide valuable insights into land system governance in China and other countries facing dietary transitions and increasing constraints on cultivated land resources.

Keywords: Dietary Demand Transition; Cropland System Resilience; Spatial Differentiation of Cropping Patterns; Food Security

1 Introduction

Arable land is the indispensable terrestrial resource foundation for food supply (Zhu et al., 2023). China supports nearly 20% of the world's population with less than 9% of the world's arable land (Niu et al., 2021; Sun et al., 2024). Global dietary consumption patterns are gradually shifting from a traditional model centered on staple foods to a more diversified pattern that includes meat, eggs, dairy, and fruits and vegetables (Zhu et al., 2024). Since 1981, the consumption ratio of staple foods, meat, poultry, eggs, and aquatic products, vegetables, and fruits among Chinese residents has shifted from 62:6:31:1 to 36:23:27:15 (Xin, 2021). This shift inevitably triggers significant changes in land resource demand, particularly in arable land cropping patterns (Wang et al., 2022). Furthermore, this may lead to resource misallocation and environmental pressures, increasing the food supply system's vulnerability (He et al., 2024). Consequently, China's arable land system governance objectives are shifting from a simple pursuit of high yields toward high resilience and sustainability (Zawalińska et al., 2021). Against this backdrop, how can we accurately assess the spatiotemporal transmission effects of dietary transition pressures on the arable land system? What state of resilience does China's arable land system exhibit under this pressure? And how can we achieve synergy between high resilience and green utilization efficiency? This gives rise to a three-pronged collaborative governance framework encompassing "dietary transition—arable land resilience—green efficiency" (Guo et al., 2025).

External disturbances provide a key entry point for understanding the resilience responses of agricultural and cropland systems. Researchers typically categorize them into two types: "sudden shocks" and "long-term stresses" (Meuwissen et al., 2019; Soriano et al., 2023). Existing research has primarily focused on sudden shocks, such as extreme weather events (e.g., droughts and floods), sharp fluctuations in market prices, trade embargoes, and public health crises (Zhang et al., 2024). Such studies mainly assess agricultural systems' ability to maintain and restore production functions under sudden shocks by analyzing system resilience and short-term output fluctuations (Li et al., 2025). Building on this foundation, further research has explored the role of these shifts—such as crop diversification, irrigation infrastructure development, and technological investments—in buffering external shocks and enhancing system resilience (Bowles et al., 2020; Dardonville et al., 2022). However, such studies focus primarily on system responses to short-term shocks and pay insufficient attention to long-term demand pressures resulting from changes in residents' dietary patterns (Tendall et al., 2015). Shifts in residents' dietary consumption trigger persistent, cumulative changes in food demand structure, continuously driving adjustments in arable land use patterns and crop structures (Shi et al., 2026). Therefore, changes in arable land demand pressures and their regional variations amid dietary transitions, as well as how arable land systems maintain and adjust their productive functions, remain worthy of further attention (Ortiz-Bobea et al., 2021).

Quantitative measures of arable land system resilience and its spatial heterogeneity are key to understanding cumulative effects and dynamic feedbacks in resilience evolution (Li et al., 2025). Existing studies have primarily constructed indicator frameworks from ecological, economic, social, and engineering perspectives. By employing multi-indicator comprehensive evaluation methods to measure the overall resilience of arable land systems, and combining tools such as spatial Markov chains and geostatistically weighted regression (GTWR), researchers have analyzed their spatiotemporal evolution, systemic coordination relationships, and influencing factors (Zha et al., 2026; Chen et al., 2024). At the same time, using spatial autocorrelation and high- and low-value

clustering analyses, these studies reveal regional differentiation and spatial clustering characteristics of arable land resilience (Wang et al., 2023). The core concept treats resilience as a key attribute for measuring an arable land system's ability to respond to disturbances and maintain its functions, providing a scientific basis for refined arable land protection and functional zoning (Wang et al., 2023). From a systemic functional perspective, arable land resilience reflects not only the ability to sustain agricultural production but also the capacity to withstand external disturbances and adapt to environmental changes; it can be understood through three dimensions: resistance, stability, and adaptability. However, existing research still has two shortcomings in revealing the internal differences in the resilience of arable land systems and their regional response characteristics. First, in terms of dimensional decomposition, most existing studies focus on comprehensive resilience assessments or the stability of a single output, making it difficult to fully reflect the asynchronous evolution of resistance, stability, and adaptability, as well as their potential trade-offs (Xu et al., 2026); Second, regarding spatial response mechanisms, while existing studies have addressed spatial variations in cropland resilience, they have paid relatively limited attention to the asymmetric responses in multidimensional resilience of cropland systems across regions with different resource endowments and socioeconomic conditions under dietary transition pressures, as well as to the changes in production functions reflected by adjustments in crop patterns (Chen et al., 2026; Ye et al., 2024).

The balance between the green efficiency of arable land use and system resilience is key to whether the system can ultimately move toward a sustainable governance path (Ye et al., 2023; Kahiluoto and Kaseva, 2016). For analytical tools and indicator development, existing studies primarily use methods such as Super-SBM or Stochastic Frontier Analysis (SFA)—which account for undesirable outputs such as carbon emissions and pollution loads—to measure the green efficiency of cropland use (Yin et al., 2022). Relevant studies emphasize that while improving agricultural production efficiency, attention should also be paid to resource conservation, ecological protection, and system resilience to promote sustainable agricultural intensification and achieve agricultural development goals consistent with the United Nations Sustainable Development Goals (SDG 2.4 and SDG 12) (Huang et al., 2025). However, existing research has paid relatively little attention to the interplay between the green efficiency of arable land use and system resilience, including potential trade-offs—particularly the possible inconsistencies between efficiency gains and enhanced ecological resilience (Lambarraa-Lehnhardt et al., 2026). Driven by the pursuit of high output efficiency, overreliance on intensive inputs such as chemical fertilizers and pesticides, or monoculture farming, may improve technical efficiency and yield stability in the short term but accelerate soil degradation and the erosion of ecological foundations, thereby leading to a "high efficiency–low resilience" fragility trap (Tamburini et al., 2020).

In summary, existing research still lacks a systematic understanding of cropland demand pressure induced by dietary transition, multidimensional resilience responses, and their coordination with green-use efficiency. In China, where constraints on cultivated land resources coexist with dietary upgrading, these research gaps are evident in three respects. (1) At the demand-transmission level, the cropland demand pressure induced by dietary transition and its dynamic relationship with multidimensional resilience remain insufficiently understood. At the same time, the asynchronous evolution of resistance, stability, and adaptability, and their potential trade-offs, have received limited attention. (2) At the spatial-response level, neglecting the asymmetric pattern of large-scale stable production in Northern China and diversified adaptation in Southern China may make it

difficult for conventional one-size-fits-all cultivated-land protection policies to accommodate regional adjustments in production functions and differentiated governance needs. (3) At the coordinated-governance level, excessive reliance on high-intensity factor inputs may intensify ecological pressure, weaken the ecological resistance of cultivated land systems, and prevent improvements in green-use productivity and system resilience from proceeding in tandem (Zawalińska et al., 2021). This may create a high-efficiency-low-resistance risk and run counter to the dual requirements of high productivity and system resilience under United Nations Sustainable Development Goal (SDG) 2.4. Clarifying how chronic dietary demand stress is transmitted to cultivated land systems, disentangling the response pathways of multidimensional resilience across the heterogeneous regions of Northern and Southern China, and addressing the coordination bottleneck in which productivity improves while resistance declines can deepen understanding of the sustainable use and governance of land systems in China and globally. Accordingly, this study aims to: (1) quantitatively measure the chronic demand stress placed on cultivated land by dietary transition and reveal its spatiotemporal transmission pathways and dynamic feedback mechanisms across the three dimensions of cultivated land resilience—resistance, stability, and adaptability; (2) disentangle the asymmetric response patterns and functional reconfiguration pathways of multidimensional cultivated land resilience arising from differences in geographic endowments between Northern and Southern China; and (3) assess the AMPI-based non-compensatory sustainability level of cultivated land green-use productivity (CLGUP) and the three resilience dimensions, address the fragility trap in which productivity improves while resistance declines, and provide scientific support for differentiated cultivated-land protection policies.

2 Theoretical analysis

Resilience reflects a system's capacity to absorb shocks, maintain key functions, and adapt to environmental change through adjustment and reorganization under external disturbances or long-term pressures (Béné et al., 2023). Unlike sudden disasters, residents' dietary transition places persistent structural pressure on cultivated land systems. As food consumption shifts from a grain-dominated pattern towards a more diverse diet, the demand for cultivated land resources associated with different food types, and the allocation of those resources, change accordingly. Consequently, the supply objectives of cultivated land systems shift from ensuring an adequate quantity of grain to jointly ensuring a stable grain supply and a diverse food supply (Alexander et al., 2015). To respond to these changes in food demand, cultivated land systems must adjust their production functions and cropping structures within the constraints imposed by resource endowments, production bases, and cropping systems (Wang et al., 2022). Regional differences in these conditions mean that cultivated land systems may develop different resilience response pathways under the same demand pressure. In regions with strong grain-production bases, favorable water and thermal conditions, flat terrain, and highly contiguous land, large-scale grain production can support stable cropping systems. Cultivated land systems in these regions rely mainly on existing production structures to maintain core grain-supply functions and buffer demand pressure. Their resilience, therefore, manifests primarily in the stable maintenance of core functions (Duan et al., 2021). By contrast, regions with more diverse cropping conditions and greater flexibility in crop allocation tend to adapt to demand changes by optimizing crop combinations and increasing crop diversity. Their resilience manifests primarily as structural adjustment (Sanford et al., 2021). Interregional

differentiation in cropping structures is therefore not merely a difference in land use; it can also be understood as differentiated resilience responses developed by cultivated land systems under a common demand pressure. Currently, cultivated land resilience is understood as comprising three interrelated dimensions. Resistance reflects the system's capacity to buffer external shocks; stability reflects its capacity to maintain continuity in grain production and cultivated land functions; and adaptability reflects its capacity to respond to changes in demand by adjusting cropping structures, input allocation, and production organization (Darnhofer, 2021; Dardonville et al., 2021).

However, a highly resilient cultivated land system is not necessarily fully sustainable. Resilience refers to the system's ability to maintain and alter its functioning under pressure. In contrast, use efficiency—which considers resource inputs, desired agricultural outputs, and undesirable environmental outputs—measures how well a cultivated land system converts resource inputs into green output performance (Shi et al., 2025). A cultivated land system can maintain food supply while improving its adaptive ability by increasing production inputs and intensifying land use. However, long-term reliance on high-intensity factor inputs increases resource consumption and environmental strain, decreasing the system's ability to operate (Pretty, 2018). Efficiency improvements can alleviate resource restrictions, but they only truly contribute to the sustainable development of cultivated land systems when combined with increased resilience (Homayounfar et al., 2022). The sustainability of cultivated land systems is thus determined not only by the levels of efficiency and resilience, but also by how well the two are aligned and coordinated (Figure 1).

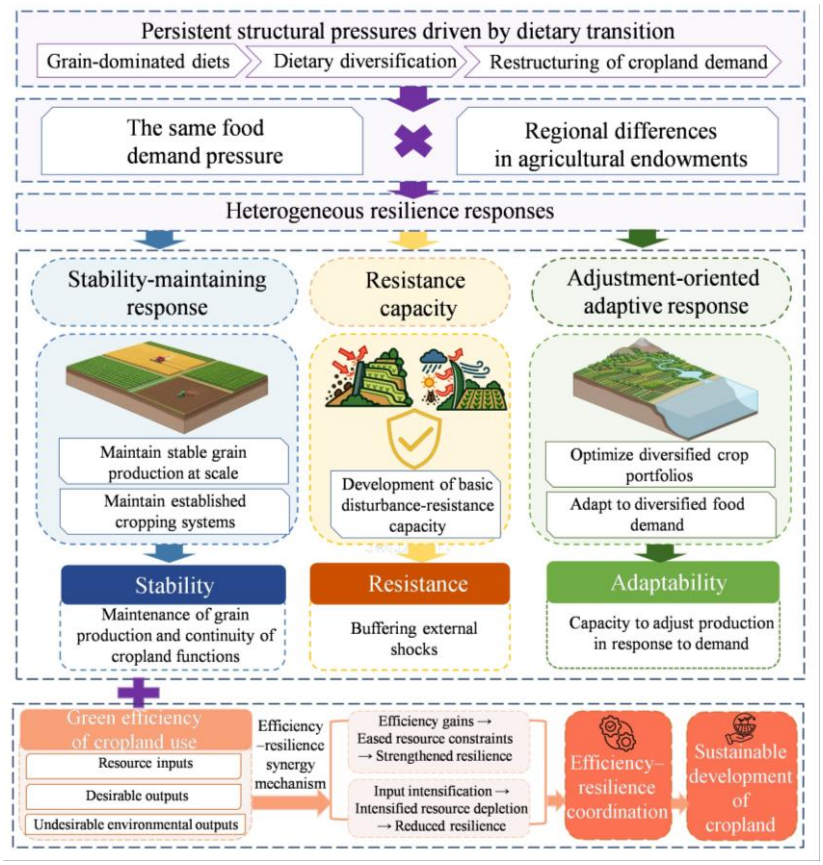


Fig. 1 Theoretical framework

3 Research area

To examine regional heterogeneity in cultivated land use, we divide 30 provincial-level administrative units in mainland China into northern and southern regions using the physical-geographical differentiation represented by the Qinling Mountains-Huaihe River Line. The study covers 2000–2024. Hong Kong, Macao, Taiwan, and Tibet are excluded because of limitations in data continuity and comparability across statistical definitions. Northern China comprises 15 provinces, including Heilongjiang, Henan, and Shandong. Overall, the region lies in temperate semi-arid and semi-humid climate zones. Although precipitation is relatively limited, extensive plains, highly contiguous cultivated land, and favorable conditions for large-scale operation make it an important production area for staple crops such as wheat and maize. Southern China also comprises 15 provinces, including Fujian, Guangxi, and Yunnan. It has a warm, humid monsoon climate and relatively abundant water and thermal resources. However, extensive hills and mountains and fragmented terrain leave cultivated land parcels relatively scattered and sloping cultivated land widespread; multiple-cropping systems and cropping structures are consequently more diverse (Figure 2). Because northern and southern China have vastly different climates and topographies, cultivated land systems with diverse cropping regimes have emerged in each region. To assess their resilience responses to dietary transition pressures, we divide the research area into northern and southern parts and do a comparison analysis to uncover these variations.

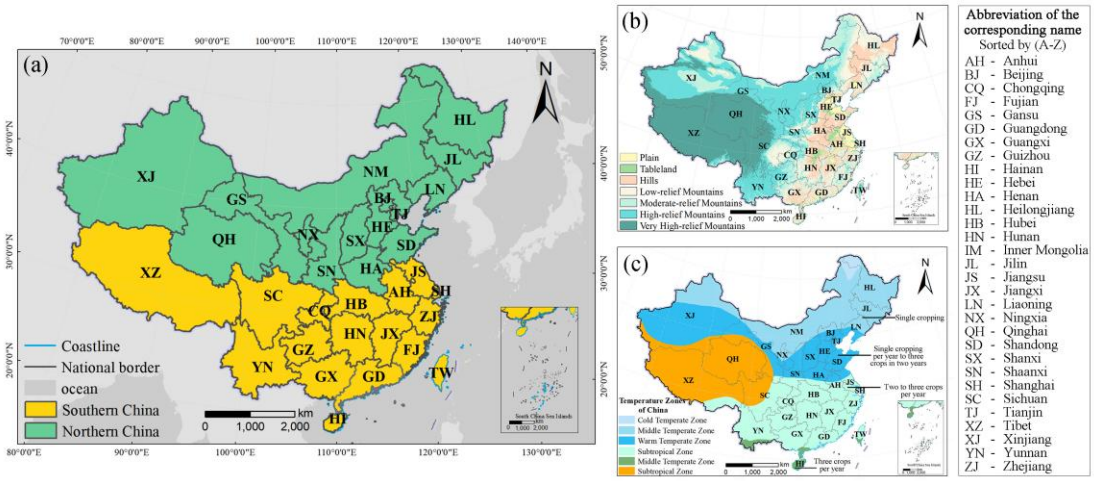


Fig. 2 Overview of the study area

4 Methodology and materials

4.1 Data and processing

We integrate provincial socioeconomic and agricultural-production statistics, gridded data on cultivated land resources and the environment, and spatial data on crop cultivation into a multi-source dataset. The dataset covers changes in cropping structures, cultivated land system resilience, cropland demand pressure under dietary transition, and green efficiency of cropland use (Table 1). Following Pan et al. (2026), we identify cropping-structure types using a threshold of 35% of crop sown area. A structure in which one crop accounts for at least 35% is classified as a single-dominant type; one in which two crops each meet the threshold is classified as a two-crop combination type. When no crop reaches 35%, the three crops with the largest shares define the combination type. We

then measure type richness as the annual number of cropping-structure types in a region divided by the total number observed over the study period; the index ranges from 0 to 1. Spatial data are extracted with a cultivated land mask and aggregated to the provincial scale. Cultivated land slope is derived from a digital elevation model (DEM), while the aggregation index and largest patch index are calculated from the spatial configuration of cultivated land. Environmental undesirable outputs are estimated parametrically. Agricultural carbon emissions cover fertilizers, pesticides, agricultural plastic film, agricultural diesel, tillage, and irrigation. Agricultural non-point-source pollution covers fertilizer losses, ineffective pesticide use, and agricultural plastic film residues. The relevant coefficients are taken from previous studies.

Table 1 Data sources

Research module	Data name	Date	Format	Source
Cropping structure and cropping patterns	Sown areas of different grain and cash crops, and total crop sown area	2000-2024	Provincial annual panel data	China Rural Statistical Yearbook and provincial statistical yearbooks
	Spatial data on cropping patterns in China	2015-2021	Raster data (500 m spatial resolution)	National Earth Observation Data Center(https://noda.ac.cn/)
	Land-use/cover data (CLCD)	2000-2024	Raster data (30 m spatial resolution)	Wuhan University China Land Cover Dataset(http://irsip.whu.edu.cn/resources/CLCD.php)
	Digital elevation model (DEM) data	2000-2024	Raster data (30 m spatial resolution)	Geospatial Data Cloud (http://gscloud.cn/)
	Soil organic carbon density data	2000-2024	Raster data (1 km spatial resolution)	National Tibetan Plateau Scientific Data Center（https://data.tpdc.ac.cn/home）
Cultivated land system resilience	Crop area affected by agricultural disasters and output of different crops	2000-2024	Provincial annual panel data	China Rural Statistical Yearbook and provincial statistical yearbooks
	Effectively irrigated area and cultivated land area	2000-2024	Provincial annual panel data	China Rural Statistical Yearbook, provincial statistical yearbooks, and China Statistical Yearbook
	Agricultural population and agricultural workers	2000-2024	Provincial annual panel data	China Rural Statistical Yearbook, provincial statistical yearbooks, and China Statistical Yearbook
	Crop-production output value, gross agricultural output value, and per-unit-area yields of different crops	2000-2024	Provincial annual panel data	China Rural Statistical Yearbook, provincial statistical yearbooks, and China Statistical Yearbook

Cropland demand pressure under dietary transition	Provincial population data	2000-2024	Provincial annual panel data	Provincial statistical yearbooks and China Statistical Yearbook
	Residents' per capita consumption of grains, meat, eggs, dairy products, aquatic products, and vegetables	2000-2024	Provincial annual panel data	Provincial statistical yearbooks and China Statistical Yearbook
	Edible proportion, food-loss rate, and grain-consumption ratio for animal-source foods	-	Model parameters	Source: Zhu et al. (2025)
Green efficiency of cropland use	Amounts of chemical fertiliser, pesticide, agricultural plastic film, and agricultural diesel used	2000-2024	Provincial annual panel data	China Rural Statistical Yearbook and provincial statistical yearbooks
	Carbon-emission factors for fertiliser, pesticide, agricultural plastic film, diesel, tillage, and irrigation	-	Model parameters	Sources: Li et al. (2011), Fang et al. (2018), and Huang et al. (2023)
	Fertiliser-loss rate, ineffective pesticide-use rate, and agricultural plastic film residue rate	-	Model parameters	Source: Fang et al. (2018)
	Crop sown area and irrigated area used to calculate carbon emissions from tillage and irrigation	2000-2024	Provincial annual panel data	China Rural Statistical Yearbook and provincial statistical yearbooks

4.2 Research framework

China's accession to the World Trade Organization (WTO) in 2001 further integrated agricultural production into international agricultural trade and increased grain production's market orientation. We therefore begin the study in 2000 and examine how China's cultivated land system resilience responds to dietary-transition pressure. We then analyze the synergy between resilience and productivity to assess system sustainability. The empirical analysis proceeds in four steps. First, using statistical yearbooks and cropping-pattern data, we classify cropping-structure types and apply

a cropping-structure type richness index and a cultivated land-use transition matrix to identify differentiation in China's cropping structures from 2000 to 2024. Second, we construct a three-dimensional resilience framework comprising resistance, stability, and adaptability, and measure provincial resilience in cultivated land using the entropy-weight method and a state-space model. Third, we construct a cropland demand pressure index to quantify pressure on cultivated land induced by changes in food consumption, and use a panel vector autoregression (PVAR) model to identify dynamic feedback between that pressure and the three resilience dimensions. Fourth, we analyze the state of sustainable development of cultivated land systems in Northern and Southern China from an efficiency-resilience synergy perspective. For this assessment, we use CLGUP, the Adjusted Mazziotta-Pareto Index (AMPI), and the coupling coordination degree model to determine whether green efficiency of cropland use and the three resilience dimensions jointly constitute a high-level, relatively balanced state of sustainable development (Figure 3).

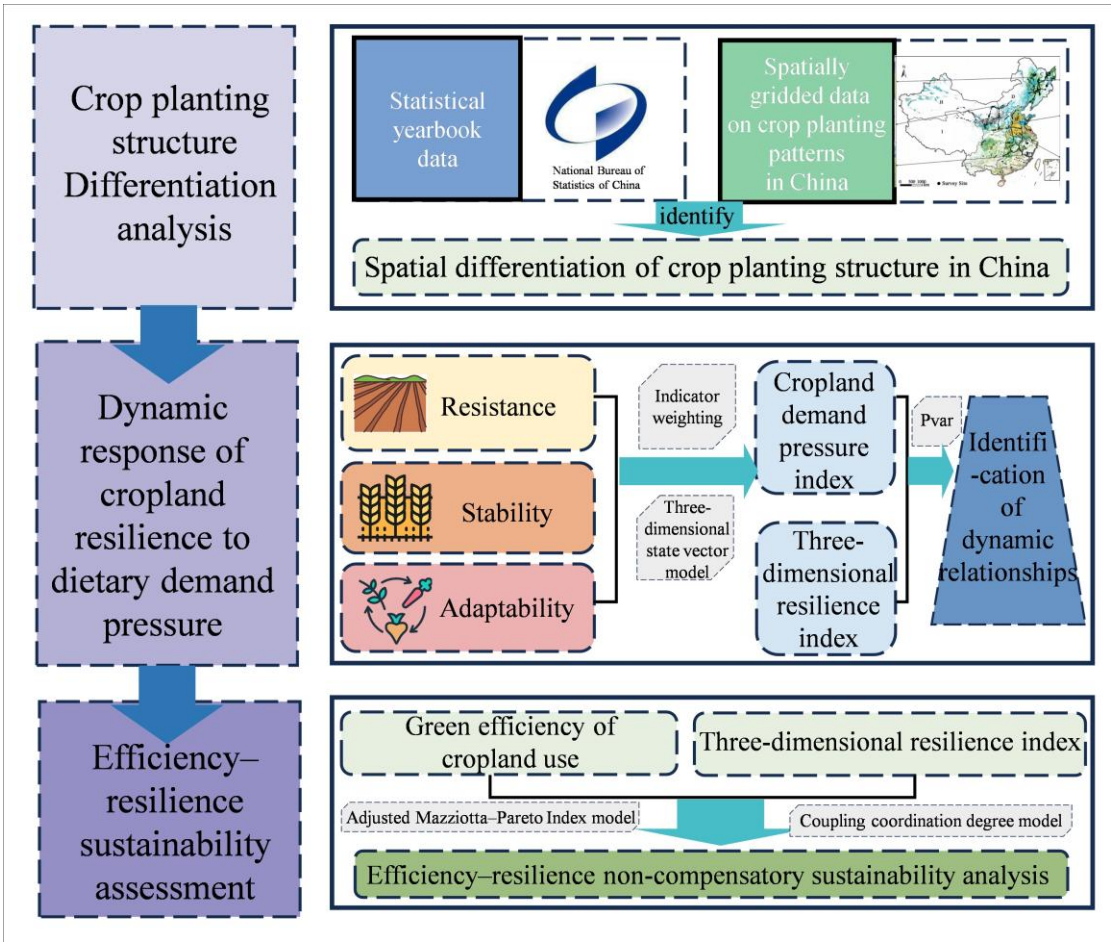


Fig. 3 Research framework

4.3 Methodology

4.3.1 Model for assessing cultivated land resilience

Resilience research increasingly acknowledges that agricultural and cultivated land systems should not be judged solely on their production capacity (Meuwissen et al., 2019). Their ability to withstand disturbances, maintain core functions, and adapt to socioeconomic and environmental change must all be considered (Béné et al., 2023; Dardonville et al., 2021). We thus develop a framework for assessing cultivated land resilience that includes resistance, stability, and adaptability.

To reduce the impact of subjective weighting, we first transform and standardize indicator directionality, and then use the entropy-weight method to calculate weights based on differences in the information provided by the indicators (Table 2).

Resistance refers to the ability of cultivated land systems to withstand external disturbances such as resource scarcity, environmental degradation, and food demand pressure. Slope represents the natural constraints on land use, whereas agricultural disaster intensity represents exposure to external disturbances. The cultivated-land aggregation index, largest patch index, and soil organic carbon density all reflect the system's natural buffering conditions via spatial structural integrity and the soil ecological foundation. Together, these conditions influence the system's ability to withstand disturbances (Reidsma et al., 2023; Soriano et al., 2023).

Stability describes a system's ability to sustain grain production and agricultural land functions over time. Effective irrigation and agricultural mechanization create favorable conditions for grain production. The percentage of grain-crop sown area shows how cultivated land resources are allocated to grain production, whereas cultivated land area per capita represents the resource base. Grain-yield stability reflects output stability in these conditions (Yin et al., 2024; Lv et al., 2025; Li et al., 2025).

Adaptability refers to a system's ability to change cropping structures, input allocation, and production organization in response to shifting demand and regional constraints. The cash-crop-to-grain sown-area ratio and the adaptability of the grain–cash crop structure indicate both the direction of adjustment and its correspondence with changes in demand. The capacity to sustain this adjustment depends on the compositional and temporal flexibility provided by crop diversity and multiple cropping, supported by the organisational capacity represented by labour productivity (Meuwissen et al., 2019; Giannakis and Bruggeman, 2018).

Table 2 Indicator system for cultivated land resilience

Dimension	Subdimension	Indicator	Calculation method or meaning	Weight
Cultivated land resilience	Resistance	Slope (-)	Extracted from DEM data obtained from the Geospatial Data Cloud	0.3200
		Cultivated-land aggregation index (AI) (+)	Calculated using ArcGIS Pro	0.0881
		largest patch index (LPI) (+)	Calculated using ArcGIS Pro	0.3121
		Agricultural-disaster intensity (-)	Crop area affected by agricultural disasters / total crop sown area × 100%	0.0566
		Soil organic carbon density (+)	Data obtained from the National Tibetan Plateau Scientific Data Center	0.2232
	Stability	Proportion of effectively irrigated area (+)	Effectively irrigated area / cultivated land area × 100%	0.2925
		Grain-yield stability (+)	$S_i = \frac{1}{CV_i} = \frac{\overline{Y_i}}{\sigma_i}$, where S_i denotes the grain-yield stability of evaluation unit i; CV_i is the coefficient of variation in grain yield; $\overline{Y_i}$ is the	0.0522

		mean grain yield over the study period; and σ_i is the standard deviation of grain yield over the study period.	
	Level of agricultural mechanisation (+)	Total power of agricultural machinery / total crop sown area	0.2251
	Share of grain-crop sown area (+)	Grain-crop sown area / total crop sown area × 100%	0.1849
	Cultivated land area per capita (+)	Cultivated land area / agricultural population	0.2453
Adaptability	Adaptability of the grain-cash crop structure (+)	Cash-crop output value / gross crop-production output value × 100%	0.1107
	Cash-crop-to-grain sown-area ratio (+)	Cash-crop sown area / grain-crop sown area	0.2124
	Crop diversity index (+)	$H=-\sum_{i=1}^{n} P_i \ln P_i$, where H is the crop diversity index; P_i is the share of the total crop-sown area accounted for by crop type i; and n is the number of crop types.	0.1664
	Multiple-cropping index (+)	Total crop sown area / cultivated land area	0.2151
	Labour productivity (+)	Gross agricultural output value / agricultural workers	0.2954

We measure the resistance, stability, and adaptability of cultivated land systems with a state-space model. Each dimension is represented by the magnitude of the vector from the state-space origin to the resilience-state point, calculated as follows:

$$\vec{P}_{it}^{r}=\sqrt{\sum_{j=1}^{m_r}(X_{ijt}^{r}\times Q_j^{r})^2} \tag{1}$$

where X_{ijt}^{r} is the standardized value for resilience dimension r and indicator j; Q_j^{r} is the weight assigned to that indicator; m_r is the number of indicators included in resilience dimension r.

为 To measure the proximity of the cultivated land system to the ideal state, the modulus of the ideal-state vector for resilience dimension r is constructed as follows:

$$p_0^{r}=\sqrt{\sum_{j=1}^{m_r}(Z_j^{r}\times Q_j^{r})^2} \tag{2}$$

where Z_j^{r} is the ideal-state value of indicator j. The ideal-state values are determined after orienting and standardizing the indicators and represent the optimum state of the cultivated land system in the corresponding resilience dimension. Accordingly, the cultivated-land resilience index is expressed as follows:

$$\mu_{it}^{r}=\frac{p_{it}^{r}}{p_0^{r}} \tag{3}$$

4.3.2 Model for measuring cropland demand pressure

To characterize the demand that residents' diversified food consumption places on cultivated land resources, we used per capita food consumption in each province and calculated demand for each food category on a common basis. The calculation accounts for the edible proportion of each food, losses during production and distribution, and the grain-conversion requirements of animal-source foods. Per capita food demand in each province was calculated using Eq. (4), and the relevant parameters are reported in Table 3.

$$G_{ijt} = \frac{x_{ijt} \times c_i}{a_i \times (1 - b_i)} \tag{4}$$

where x_{ijt}, （i =1,2,...,6）denotes the per-capita consumption of grain, meat, eggs, dairy products, aquatic products, and vegetables, respectively, in province j in year t; a_i is the edible portion ratio; b_i is the loss rate; and c_i is the grain-conversion rate.

Table 3 Parameters used to calculate food demand

Calculation parameter	Cereals	Meat	Eggs	Milk	Aquatic products	Vegetables
Edible proportion	93.80	65.90	85.00	100.00	55.60	88.00
Loss rate	2.50	15.00	10.00	6.00	34.00	20.00
Grain-conversion rate	1.00	2.54	1.68	0.37	1.28	-

Cropland demand arising from residents' diversified food consumption depends on both the scale of food demand and regional grain-production capacity. Following previous studies (Sun et al., 2024; He et al., 2024), we calculated food-consumption-induced cropland demand as follows:

$$L_{jt} = \frac{p_{jt} \times \sum_{i=1}^{6} (A_i \times G_{ijt})}{U_{jt} \times R_{jt} \times E_{jt}} \tag{5}$$

where L_{jt} is the food-consumption-induced cropland demand; P_{jt} is the population of province j in year t; A_i is the food self-sufficiency rate; U_{jt} is the yield per unit sown area in the relevant province and year; R_{jt} is the grain-sown area as a share of cultivated land area in province j in year t; E_{jt} is the multiple-cropping index of province j in year t.

We used the food-consumption-induced cropland pressure index to measure the match between residents' food-consumption demand and cropland supply capacity. Defined as the ratio of the cropland area required for food consumption to the actual cultivated land area, the index captures provincial cropland pressure in China from 2000 to 2024. It was calculated as follows (Xiong et al., 2025):

$$P_{jt} = \frac{L_{jt}}{\text{Area_Cropland}_{jt}} \tag{6}$$

An index value greater than 1 indicates that the cultivated land area required for food consumption exceeds the actual cultivated land area, implying an insufficient regional supply of cultivated land and greater dependence on external supply. A value below 1 indicates that existing cultivated land can meet residents' food-consumption demand and therefore provides relatively strong supply security.

4.3.3 Panel vector autoregression model

To examine dynamic feedback between cropland demand pressure and cultivated land resilience as dietary demand changes, we constructed a panel vector autoregression (PVAR) model. Generalized method of moments (GMM) estimation was used to estimate lagged effects among the variables, and impulse response functions were used to trace the dynamic response to shocks. The model is specified as follows:

$$Y_{it} = \alpha_0 + \sum_{j=1}^{p} A_j Y_{i-j} + \mu_i + \lambda_t + \varepsilon_{it} \tag{7}$$

where $Y_{it} = (CDP_{it}, RES_{it}, STA_{it}, ADA_{it})'$ is the variable vector for province i in year t; within this vector, CDP_{it} is the cultivated-land demand pressure for province i in year t; RES_{it} denotes resistance; STA_{it} denotes stability; ADA_{it} denotes adaptability; p is the lag order; A_j is the coefficient matrix for lag j; μ_i and λ_t denote the individual and time effects, respectively; and ε_{it} is the random disturbance term.

4.3.4 Measuring green efficiency of cropland use

To measure changes in green efficiency of cropland use (CLGUP) under the joint influence of inputs, desirable outputs, and environmental constraints, we combined the epsilon-based measure (EBM) directional distance function with the global Malmquist-Luenberger (GML) productivity index. The model is specified as follows (Huang et al., 2025):

$$\begin{aligned} GML^{t,t+1}(x^t, y^t, b^t, x^{t+1}, y^{t+1}, b^{t+1}) &= \frac{1 + D^G(x^t, y^t, b^t)}{1 + D^G(x^{t+1}, y^{t+1}, b^{t+1})} \\ &= \frac{1 + D^t(x^t, y^t, b^t)}{1 + D^{t+1}(x^{t+1}, y^{t+1}, b^{t+1})} \times \left[\frac{\left[(1 + D^G(x^t, y^t, b^t)\right] / \left[1 + D^t(x^t, y^t, b^t)\right]}{\left[1 + D^G(x^{t+1}, y^{t+1}, b^{t+1})\right] / \left[1 + D^{t+1}(x^{t+1}, y^{t+1}, b^{t+1})\right]} \right] \\ &= EC^{t,t+1} \times TC^{t,t+1} \end{aligned} \tag{8}$$

where x denotes the inputs to cultivated-land use; y denotes the desirable outputs from cultivated-land use; b denotes the undesirable outputs from cultivated-land use; $D(x, y, b)$ is the directional distance function; and t and $t+1$ denote two consecutive years.

Using 2000 as the base year, we cumulatively multiplied the period-specific GML indices to construct provincial CLGUP series for 2000-2024 and used ArcGIS spatial analysis tools to examine their spatiotemporal evolution. To capture the food-supply capacity of cultivated land systems under dietary transition, the indicator system comprises inputs, desirable outputs, and undesirable outputs. Crop-sown area, labor input, and agricultural intermediate consumption are used as input indicators. Desirable outputs comprise grain, vegetable, oil-crop, and sugar-crop production, whereas undesirable outputs comprise agricultural carbon emissions and agricultural non-point-source pollution (Table 4).

Table 4 Indicator system for green efficiency of cropland use

Type	Indicator name	Unit
Input	Crop-sown area	hectares (ha)
	Labor Input	persons
	Agricultural Intermediate Consumption	100 million CNY
Desirable output	Grain production	10,000 tons
	Vegetable production	10,000 tons

	Oil-crop production	10,000 tons
	Sugar-crop production	10,000 tons
Undesirable output	Carbon emissions	10,000 tons
	Non-point-source pollution	10,000 tons

4.3.5 Evaluating efficiency-resilience coordinated sustainability

To prevent a high value in one dimension from masking weaknesses in others, we used the Adjusted Mazziotta-Pareto Index (AMPI) (Mazziotta and Pareto, 2016). By reducing the influence of uneven development across dimensions on the composite assessment, AMPI reflects the importance of balanced development within the cultivated land system. We therefore assessed CLGUP, stability, adaptability and resistance in terms of both their overall level and their balance across dimensions. The index was calculated as follows:

$$Z_{ijt} = 70 + 60 \times \frac{X_{ijt} - X_j^{\min}}{X_j^{\max} - X_j^{\min}} \tag{9}$$

$$M_{it} = \frac{1}{n}\sum_{j=1}^{n} Z_{ijt} \tag{10}$$

$$S_{it} = \sqrt{\frac{1}{n}\sum_{j=1}^{n}(Z_{ijt} - M_{it})_2} \tag{11}$$

$$CV_{it} = \frac{S_{it}}{M_{it}} \tag{12}$$

$$AMPI_{it} = M_{it} - S_{it} \times CV_{it} \tag{13}$$

where X_{ijt} and Z_{ijt} denote, respectively, the raw and standardized values for the relevant dimension in province i in year t; $X_j^{\min}$ and $X_j^{\max}$ are, respectively, the minimum and maximum values of dimension j over the study period; M_{it}, S_{it}, and CV_{it} represent the mean, standard deviation, and coefficient of variation of the four-dimensional system, respectively; n is the number of evaluation dimensions, set here to $n = 4$. Because all four dimensions are positive indicators, the positive AMPI model is used. A higher AMPI value indicates a higher overall level and a more balanced internal structure of the CLGUP–resilience system. The 25th, 50th, and 75th percentiles of AMPI values over the study period are then used to classify AMPI-based non-compensatory sustainability levels (Table 5).

Table 5 Classification of AMPI-based non-compensatory sustainability levels

AMPI quantile criterion	AMPI-based sustainability type
$AMPI_{it} < Q_{25}$	Low-level constrained type
$Q_{25} \le AMPI_{it} < Q_{50}$	Medium-low-level type
$Q_{50} \le AMPI_{it} < Q_{75}$	Medium-high-level type
$AMPI_{it} > Q_{75}$	High-level advantageous type

We further used the coupling coordination degree model to assess whether CLGUP develops in coordination with each resilience dimension. The model was calculated as follows:

$$C_{kit} = \left\{ \frac{E_{it} \times R_{kit}}{\left[(E_{it} + R_{kit}) / 2 \right]^2} \right\}^{1/2} \tag{14}$$

$$T_{kit} = \alpha E_{it} + \beta R_{kit} \tag{15}$$

$$D_{kit} = \sqrt{C_{kit} \times T_{kit}} \tag{16}$$

where E_{it} denotes green efficiency of cropland use (CLGUP) for province i in year t; R_{kit} denotes the standardized cultivated land resilience value for province i in year t and resilience dimension k; k indexes resistance, stability, and adaptability, respectively; C_{kit}, T_{kit}, and D_{kit} denote, respectively, the coupling degree, composite coordination index, and coupling coordination degree. Because this study considers CLGUP and resilience equally important to the sustainable development of cultivated land systems, they are assigned equal weights; thus, $\partial = \beta = 0.5$. A higher D value indicates stronger coordination between CLGUP and resilience; the classification criteria are provided in Table 6.

Table 6 Coupling and coordination degree classification criteria

Coupling and coordination interval values	Coupling and coordination types
0≤D＜0.2	Serious disorders
0.2≤D＜0.4	Mild disorders
0.4≤D＜0.6	Primary coordination
0.6≤D＜0.8	Intermediate coordination
0.8≤D＜1	Quality coordination

5 Results

5.1 Evolution of cropping structures on China's cultivated land

5.2 Dynamic responses of cultivated land resilience to dietary-transition pressure

5.2.1 Spatiotemporal evolution of cultivated land resilience

Between 2000 and 2024, cultivated land resilience in China differed markedly across dimensions and between Northern and Southern China. Stability was stronger in the north: its multi-year mean was 1.058, compared with 0.878 in the south. Northern stability increased from 0.803 to 1.417 (76.4%), while southern stability rose from 0.656 to 1.243 but remained lower (Figure 5b). In 2024, stability increased markedly in major northern grain-producing provinces such as Heilongjiang, Inner Mongolia and Shandong. This improvement was attributed to the favorable conditions for stable grain production provided by contiguous cultivated land, large-scale farming and stable staple-grain cropping systems (Figure 5a). Adaptability, by contrast, remained higher in Southern China. Its multi-year mean was 1.354, compared with 1.027 in the north, and it increased from 1.134 in 2000 to 1.562 in 2024 (a 37.7% increase). Northern adaptability fell from 0.978 to 0.896. These results indicate that Southern China relied more on cash crops, specialized agriculture, and multiple-cropping systems to respond to changing food demand (Figure 5a). Resistance declined in both regions, from 1.312 to 1.213 in the north and from 1.142 to 1.08 in the south. Thus, even as production functions and adaptability improved, the spatial patterns of cultivated land, resource quality, and ecological support capacity were subject to some disturbance.

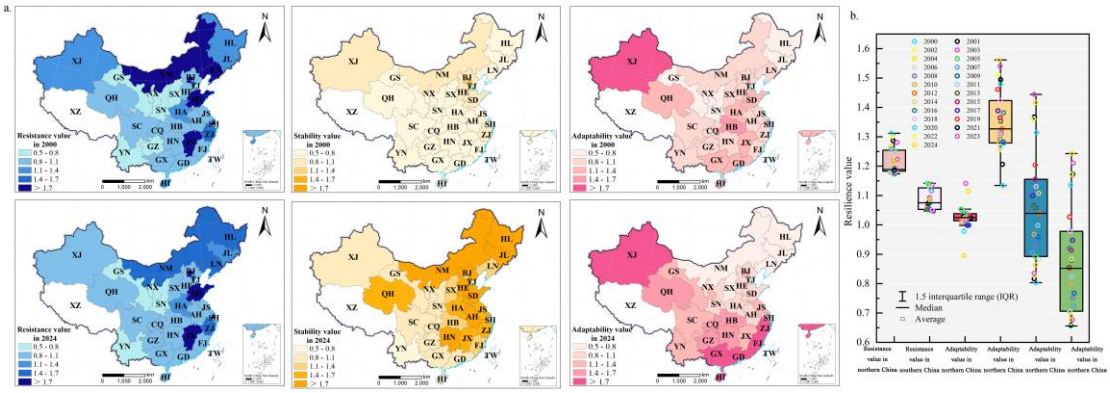


Fig. 5 Regional differentiation and spatiotemporal evolution of three-dimensional cultivated land resilience in China. (a) Regional differentiation, 2000-2024; (b) spatiotemporal evolution, 2000-2024.

5.2.2 Spatiotemporal evolution of cropland demand pressure under dietary transition

Changes in residents' food consumption drove a broad rise in cropland demand pressure (Figure 6). The national cropland pressure index increased from 1.42 to 2.34, while the number of provinces with values above 1 rose from 12 to 17, with Zhejiang, Fujian, Guangdong, Guangxi and Hainan accounting for the three additional provinces. Overall, food-consumption-induced demand shifted from a critical state to an overload state. The median also rose, from 0.70 to 1.06, indicating that the increase was widespread rather than driven by only a few high-pressure provinces. High-pressure areas were concentrated in eastern coastal and megacity regions, including Beijing, Shanghai and Zhejiang, and in ecologically constrained regions such as Qinghai, Gansu and Ningxia. Low-pressure areas were concentrated in major grain-producing provinces such as Heilongjiang, Jilin and Henan. The shift from grain-dominated diets towards more diversified consumption of animal-source foods, vegetables and fruit therefore increased both total cropland demand and its regional differentiation. Pressure has risen in most southern provinces, for example, from 0.58 to 5.63 in Zhejiang and from 0.64 to 2.90 in Fujian. This may be related to the growing demand for diverse foods, compounded by constraints such as limited arable land and fragmented plots. Pressure declined in most northern provinces; in Heilongjiang, for example, it fell from 0.86 to 0.25. More favorable conditions for large-scale cultivation and a stronger grain production base may have buffered demand pressure in the north (Figure 6).

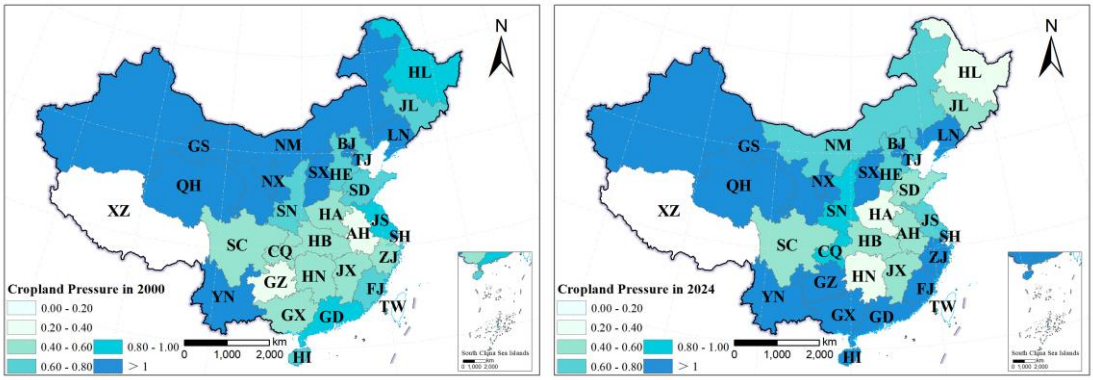


Fig. 6 Spatiotemporal evolution of cropland pressure in China

5.2.3 Dynamic responses of resilience to cropland demand pressure

PVAR model tests for the northern and southern samples are reported in the Supplementary

Materials (Tables S1-S6 and Figure S1). In Southern China, cultivated land systems responded to dietary demand pressure with short-term declines in stability and resistance, alongside adjustments through adaptability (Figure 7). Cropland demand pressure lagged by one period had a significant negative effect on stability (5% level; coefficient, -0.015). Following a pressure shock, stability responded negatively in period 1, declined more markedly around period 2, and then gradually approached zero. Lagged cropland demand pressure also had a significant negative effect on resistance (5% level; coefficient, -0.015). Resistance declined in the short term following the shock, then gradually approached its earlier level. A short-term rise in food-consumption pressure may therefore weaken the system's buffering capacity before management adaptation takes effect. Adaptability lagged by one period had a significant positive effect on itself (5% level; coefficient, 0.191). This continuity indicates that the adjustment capacity generated by diversified cropping in Southern China can continue to respond to changes in cropland demand.

The relationship between pressure on arable land demand and resilience in northern regions is primarily defined by dynamic features such as stability response, resistance support, and adaptive synergy. (Figure 8). Cropland demand pressure lagged by one period had a significant negative effect on stability (10% level; coefficient, −0.008). Stability declined in the short term and then gradually approached zero. Effects on resistance and adaptability were not significant, and their impulse responses were small. The three resilience dimensions, however, were positively associated. Resistance lagged by one period had a significant positive effect on stability (5% level; coefficient, 0.106), while stability had a significant positive effect on adaptability (10% level; coefficient, 0.151). Northern cultivated land systems thus responded to demand pressure mainly through stability, with resistance supporting stable production. Stronger grain production stability not only secured basic supply but also preserved the scope for further adjustment to changing demand.

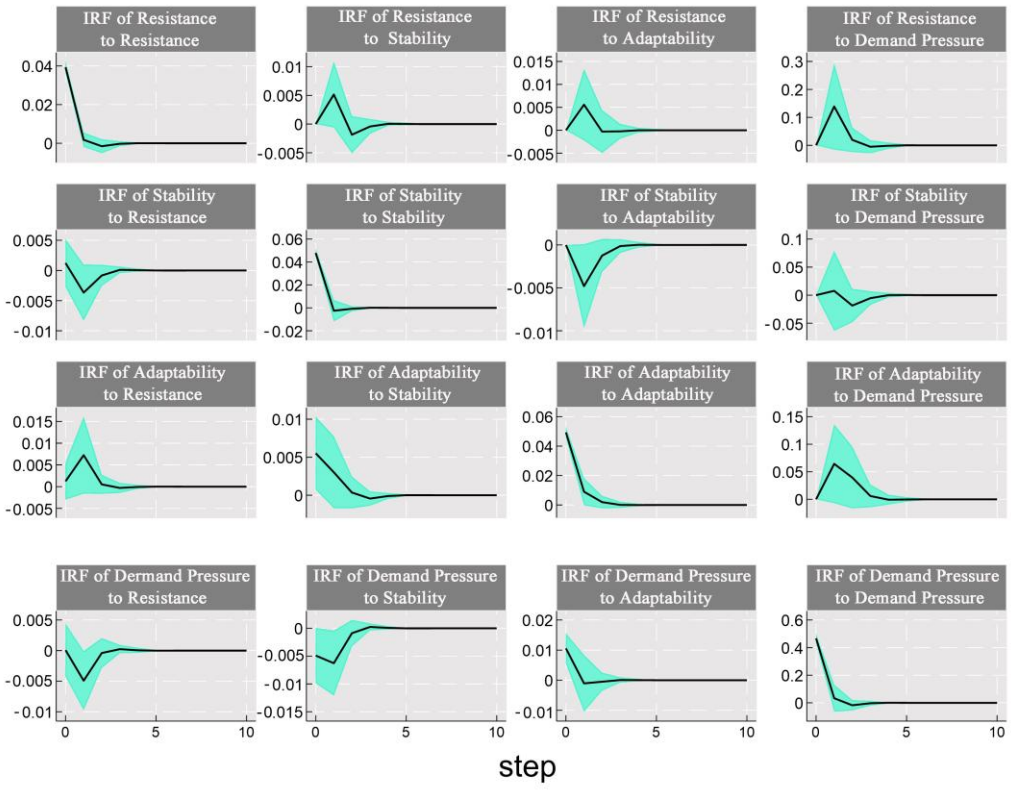


Fig. 7 Impulse responses for Southern China

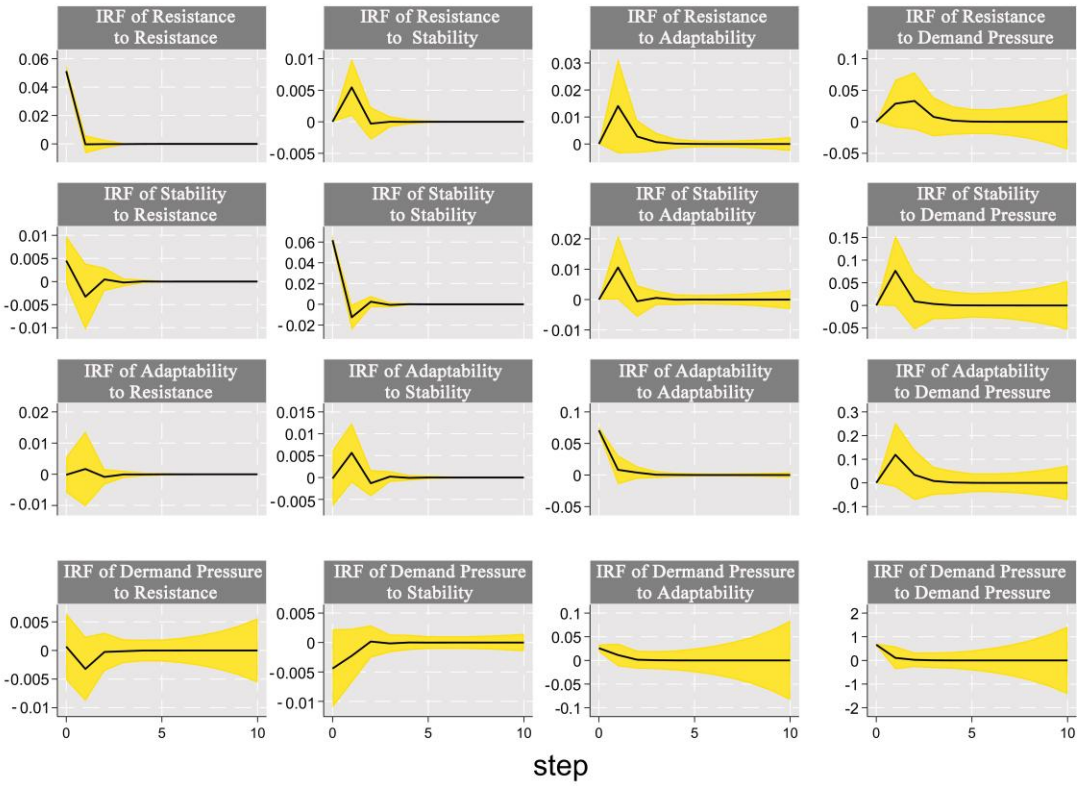


Fig. 8 Impulse responses for Northern China

5.3 Sustainability and coordination between green efficiency of cropland use and resilience

Between 2000 and 2024, green efficiency of cropland use (GUGE) in China rose overall, albeit with fluctuations and marked regional differentiation. The national mean increased from 0.538 to 0.592, indicating a gradual improvement in cultivated-land output performance under resource and environmental constraints (Figure 9b). The standard deviation increased from 0.174 to 0.199, indicating that interprovincial disparities widened. In 2024, high GUGE values were concentrated in two groups of regions (Figure 9a). Eastern coastal regions such as Shanghai, Jiangsu and Zhejiang combined agricultural facilities, intensive operation and technological capacity to achieve high output performance despite cultivated-land resource constraints. Inner Mongolia and Xinjiang represented a second group with a strong basis for large-scale farming. GUGE increased more in Southern China than in Northern China: the regional mean rose from 0.545 to 0.629 in the south, compared with 0.530 to 0.554 in the north. Together with the preceding cropping-structure results, this pattern suggests that Southern China's diversified production systems may have supported productivity gains.

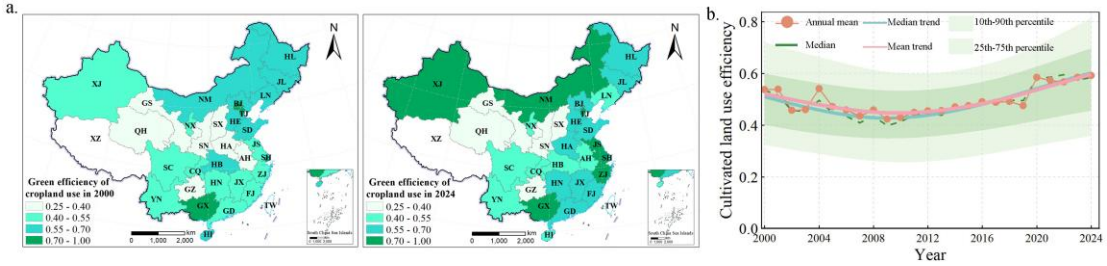


Fig. 9 Trends and spatiotemporal evolution of green efficiency of cropland use in China. (a) Spatiotemporal

evolution; (b) national trend, 2000-2024.

The efficiency-resilience AMPI rose from 84.823 to 91.950, indicating an overall increase in the AMPI-based non-compensatory sustainability level. The number of high-level advantageous provinces increased from 6 to 18, while the number of low-level constrained provinces decreased from 11 to 4. The standardized mean across the four dimensions rose from 86.057 to 93.570, but the coefficient of variation increased from 0.106 to 0.123. Improvements were therefore asynchronous, and the system evolved unevenly (Figure 10b). In Northern China, the number of high-level advantageous provinces increased from 4 to 8, and the number of low-level constrained provinces decreased from 5 to 3 (Figure 10a). Inner Mongolia's AMPI rose from 88.508 to 99.638. Its standardized GUGE and stability values reached 115.539 and 117.877, respectively, whereas adaptability was 77.1312. Northern advantages thus lay primarily in higher GUGE and maintained grain-production stability. Improvement was more pronounced in Southern China, where the number of high-level advantageous provinces increased from 2 to 10, and the number of low-level constrained provinces decreased from 6 to 1. Zhejiang's AMPI rose from 86.832 to 104.080, and its structural status shifted from mildly unbalanced to balanced development. Guangxi, Jiangsu, and Fujian reached AMPI values of 98.384, 94.831, and 91.718, respectively, and all entered the high-level advantageous category. Despite increases in GUGE, stability, and adaptability across Southern China, resistance fell by 1.774. In Fujian, Guangdong, and Hunan, increases in GUGE and adaptability exceeded changes in resistance, indicating that Southern China still needs to optimize cultivated-land spatial patterns, improve resource quality, and strengthen ecological support capacity.

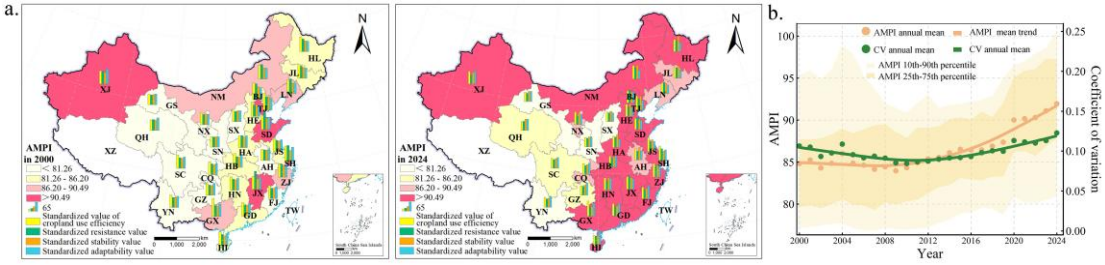


Fig. 10 Spatiotemporal differentiation and evolution of the AMPI-based non-compensatory sustainability level for green efficiency of cropland use and resilience in China. (a) Spatiotemporal differentiation in the sustainability level and standardised four-dimensional mean; (b) trends in AMPI and its coefficient of variation, 2000-2024.

Building on the AMPI analysis, the coupling coordination results further reveal the relationship between GUGE and three-dimensional resilience (Figure 11). From 2000 to 2024, coordination generally improved. The greatest improvement was between GUGE and stability: their mean coupling coordination degree increased from 0.451 to 0.671, a 48.9% increase. The number of provinces with high or moderate coordination increased from 3 to 21, while those with mild imbalance fell from 9 to 0. Productivity gains and stable grain production thus moved from low towards higher coordination. High coordination was concentrated in Northern China's major grain-producing regions. By 2024, 11 of the 15 northern provinces had reached a high or moderate level of coordination. Inner Mongolia and Heilongjiang entered the high-coordination category, with values rising from 0.520 and 0.531 to 0.883 and 0.880, respectively. This pattern may reflect concentrated staple-grain production, contiguous cultivated land, and advantages in large-scale farming. From 2000 to 2024, coordination between GUGE and adaptability also improved. The number of moderately coordinated provinces rose from 7 to 11, and the number with high

coordination rose from 0 to 4. High coordination was concentrated in Southern China, where 11 of the 15 provinces had reached moderate or high coordination by 2024. Guangxi and Zhejiang entered the high-coordination category, with values rising from 0.752 and 0.560 to 0.915 and 0.826, respectively. Productivity gains were therefore strongly coordinated with a greater capacity to adapt to changing food demand. In contrast, the improvement in coordination between GUGE and resistance was limited. From 2000 to 2024, the number of provinces with moderate or higher coordination fell from 13 to 12, and Gansu, Shaanxi, Qinghai, and Shanxi remained mildly imbalanced.

Overall, Northern China followed a stable grain-supply pathway characterized by higher GUGE and greater stability. Southern China followed a pathway of cropping-structure optimization and demand adaptation supported by higher GUGE and adaptability. Both improved the response of cultivated land systems to changes in dietary structure, but each also revealed a distinct constraint. Northern systems need greater adaptive flexibility while maintaining production stability, whereas southern systems need to prevent productivity-oriented diversification from weakening resistance and ecological security.

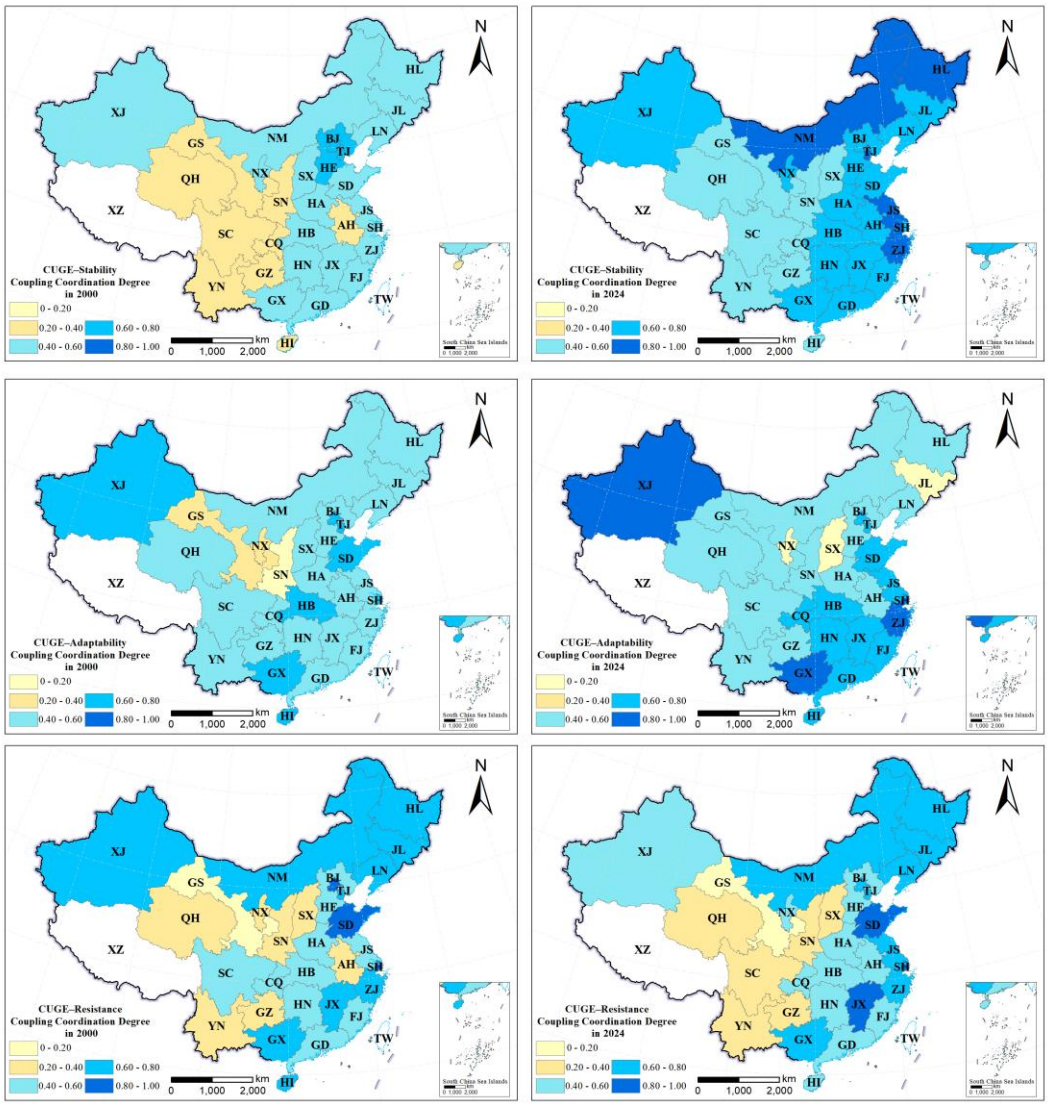


Fig. 11 Spatiotemporal differentiation in coupling coordination between green efficiency of cropland use and three-dimensional cultivated land resilience in China

6 Discussion

6.1 Differentiated resilience governance for northern and southern cultivated land systems under dietary-transition pressure

As diets shift from staple foods towards diversified consumption of meat, eggs, milk, vegetables, fruit, and aquatic products, feed-grain demand rises and pressure on cultivated-land supply increases. The cultivated land required to support residents' diets reportedly expanded from 99.44 Mha in 1987 to 159.66 Mha in 2021, exceeding the existing resource base (Zhu et al., 2025). Against this backdrop, China's crop production has gradually evolved into a pattern characterized by "stable staple crop production in the north and diversified supply in the south." (Duan et al., 2021). Our findings further show that northern and southern cultivated land systems respond differently to dietary-transition pressure. Northern China relies mainly on production stability, supported by relatively contiguous cultivated land, large-scale farming, and staple-grain systems such as wheat-maize production. Southern China relies more on diversified cropping systems, specialized agriculture, and integrated cropping systems to adapt to changing food demand. Its favorable hydrothermal conditions and potential for two or three crops per year allow cultivated land to support richer crop combinations and cropping patterns. Compound cultivated-land use combines grain crops with cash crops such as fruit and vegetables within the same land unit through temporal and spatial arrangements including crop rotation, intercropping and relay intercropping. Institutionally, the Current Land Use Classification (GB/T 21010-2017) permits the intercropping or relay intercropping of fruit trees, tea plants, and similar crops on cultivated land, provided that the cultivated layer is not damaged and either coverage is $\leqslant$50% or plant numbers per mu are $\leqslant$ 70% of the reasonable density. At the level of planting principles, three-dimensional management can achieve a diverse supply of fruits, vegetables, and other crops by expanding production space without reducing arable land (Liang et al., 2026). From the perspective of empirical benefits, agroforestry, intercropping, and crop rotation can collectively enhance ecosystem services, land-use efficiency, stable production and yield capacity, and farmers' income, achieving a synergistic improvement in ecological, production, and economic benefits. (Deng et al., 2024). Resilience governance should therefore be regionally differentiated. Northern China should protect high-quality grain-production bases while strengthening adaptability through technological innovation and more efficient resource use. Southern China should retain the flexibility of diversified compound production while preventing land fragmentation, soil quality degradation, and the accumulation of ecological pressures that would weaken long-term resilience.

6.2 Comparison with existing studies

International experience indicates that resource endowments, production organization, and risk exposure jointly shape the relationship between productivity and resilience. In large-scale North American grain systems, including those of the United States and Canada, productivity gains depend mainly on mechanization, scale, and technological progress. Yet intensive production may simplify cropping structures and homogenize landscapes, limiting adaptation to climate change (Hufnagel et al., 2020). Bowles et al. (2020) found that greater crop-rotation diversity can maintain both yields and drought resistance, showing that productivity and resilience need not be trade-offs. Regions exposed to greater climatic risk, such as India, rely more on crop diversification to buffer production

risks from high temperatures and insufficient precipitation (Birthal and Hazrana, 2019). Although these studies differ from ours in scale and indicator systems, they consistently indicate that productivity gains support long-term sustainability more effectively when coordinated with production stability, adaptive adjustment, and the resource base. Lambarraa-Lehnhardt et al. (2026) similarly found comparable mean technical efficiency but markedly different resilience among farms in Spain and Algeria, confirming that the two do not necessarily change in tandem. China faces the combined requirements of cultivated-land resource constraints, dietary-demand transition, and food-security protection. We found stronger coordination between GUGE and stability in Northern China and between GUGE and adaptability in Southern China, indicating differentiated productivity-resilience coordination pathways. Coordination between GUGE and resistance improved less. This pattern is consistent with China's high resource and environmental input pressures. In 2022, agricultural fertilizer consumption exceeded 50 million tonnes, and application reached 429 kg/hm²; pesticide application in 2019 was 8.7 kg/hm², approximately 3.3 times the global average (Zhang et al., 2025). Productivity gains thus remain associated with high resource and environmental pressure. Sustainable cultivated-land development in China should therefore pursue neither productivity growth nor a single resilience advantage in isolation, but coordinated improvements in productivity, stability, adaptability and resistance. This is consistent with SDG 2.4, which jointly emphasizes productivity, resilient agricultural practices, ecosystem maintenance and improved land quality.

6.3 Limitations and future research

This study has several limitations. First, the province is the main unit of analysis. Although this scale reveals overall national and regional patterns, it may conceal heterogeneity across counties, farm households and plots. Second, the cropland pressure index focuses on major food categories and does not fully incorporate food waste, eating away from home or interprovincial virtual cultivated-land flows. Future analyses that include these factors could better explain the link between consumption-side transition and production-side cropland demand. Third, the PVAR model can identify dynamic interactions between pressure and resilience, but its causal mechanisms could be further tested through quasi-experimental designs, scenario simulations or sensitivity tests under alternative dietary assumptions.

7 Conclusions

As Chinese diets shift from staple grains towards greater diversity and nutritional value, this study examines how cultivated land systems can accommodate expanding food demand while maintaining production functions and improving resource-use efficiency. Using data from 30 provincial-level administrative units in mainland China, we analyzed the evolution of cropping structures and consumption-driven pressure on cropland demand, measured resistance, stability, and adaptability, and examined the collaborative relationship between green efficiency of cropland use and multidimensional resilience. China's cultivated land systems exhibited pronounced north-south differentiation, with distinct patterns of functional reconfiguration and resilience response. First, cropping structures became more regionally differentiated: Northern China became increasingly oriented towards staple-grain production, whereas Southern China shifted towards diversified, adaptive cropping systems. Second, cropland demand pressure increased significantly from 2000 to 2024, with high-pressure areas concentrated in coastal and highly urbanized regions, as well as in

areas subject to strong ecological constraints. Third, resilience diverged across dimensions. Stability was stronger in Northern China and adaptability higher in Southern China, while resistance faced downward pressure in both regions. Fourth, GUGE increased overall, but productivity gains did not fully coincide with stronger resilience; resistance remained a particular weakness. Cultivated-land governance under dietary transition should therefore move beyond quantitative protection towards coordinated governance that integrates demand pressure, production stability, adaptive reconfiguration, ecological resistance and productivity gains.

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Author contributions
Chenyan Lin (First Author): Data curation, Formal analysis, Methodology, Software, Validation, Visualization, Writing-original draft; Zhen Xie (Corresponding Author): Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Software, Validation, Writing – review & editing; Quan Zhou: Investigation, Project administration, Resources, Software, Supervision, Validation, Visualization.

Competing interests
The authors declare no competing interests.

Data availability
The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

Ethical approval
This article does not contain any studies with human participants performed by any of the authors.

Informed consent
We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

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