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RESEARCH ARTICLE

Spatiotemporal dynamics and food security implications of cropland abandonment in China

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Highlights

- China's cropland abandonment rate peaked at 3.98% in 2016, exhibiting four distinct phases.
- Three abandonment patterns were classified: long-term (≥10 years), progressive, and occasional types.
- High abandonment rates (>15%) are concentrated in mountainous regions while plains maintain rates below 5%.
- Abandoned cropland resulted in peak potential grain losses of 23.8 million tonnes in 2010.

Abstract

Cropland abandonment substantially affects food security and agricultural sustainability, yet comprehensive analyses of its dynamics in rapidly developing regions remain limited. This study examines the spatiotemporal patterns, labor migration influences, and food security implications of cropland abandonment in China from 1992 to 2022. The results show that abandonment progressed through four phases: slow growth, rapid increase, high-level fluctuation peaking at 3.98% in 2016, and gradual decline. The research identified three primary abandonment patterns — single long-term (≥10 years), progressive degradation, and occasional (3–9 years) — with distinct spatial distributions. Long-term abandonment concentrates in the marginal agricultural areas of southwestern mountainous regions, while occasional abandonment predominates in the more economically developed eastern coastal areas, and progressive degradation patterns appear in transitional zones between plains and mountains. Labor migration influenced abandonment non-linearly with distinct regional thresholds. Short-distance (within-county) migration reduced abandonment rates, while medium-distance (within-province) migration significantly increased them. Although 57.50% of abandonment occurred on low-suitability land, 42.50% affected high-suitability cropland, resulting in peak potential grain losses of 15.0 and 8.8 million tonnes for low and high suitability land respectively in 2010. These findings support regionally differentiated land management strategies that integrate land suitability assessments, labor migration patterns, and local socioeconomic conditions to ensure agricultural sustainability.

Keywords: cropland abandonment, land use trajectory, food security, agricultural land suitability, China

1. Introduction

Croplands are essential to global food security and sustainable rural development, comprising approximately 13% of Earth's terrestrial surface (Rudel *et al.* 2009; Potapov *et al.* 2021). However, since the mid-20th century, a paradoxical phenomenon has emerged, while agricultural land intensification persists in some areas, substantial cropland abandonment occurs in others (Li *et al.* 2018; Potapov *et al.* 2021; Zheng *et al.* 2023). Recent satellite-based assessments indicate that while 217 Mha of cropland expansion occurred globally from 2003 to 2019, approximately 79 Mha of existing cropland was abandoned (Bren d'Amour *et al.* 2017; Zheng *et al.* 2023). This widespread abandonment has substantial implications for food security, ecosystem services, and sustainable rural development (Cramer *et al.* 2008; Meyfroidt 2016). In Europe, approximately 52.5 Mha of agricultural land were abandoned by 2005 (Queiroz *et al.* 2014; Liu and Li 2017),

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while post-Soviet countries experienced the abandonment of about 31% (57 million hectares) of their former cropland between 1991 and 2000 (Prishchepov *et al.* 2012; Meyfroidt 2016).

In China, cropland abandonment represents a complex socio-ecological transformation influenced by multiple factors (Han and Song 2019, 2020; Grabska-Szwagrzyk *et al.* 2024). At the national level, rapid urbanization (projected to increase from 60.6% in 2020 to approximately 70% by 2035) (Ning *et al.* 2022) and rural aging (Liao *et al.* 2019) are driving substantial demographic changes (Gu *et al.* 2017; Kriebs 2023; Ren *et al.* 2023). Labor migration constitutes a critical aspect of these changes, with approximately 293 million rural migrant workers in 2021 (NBSC 2022), fundamentally transforming rural labor availability and agricultural production systems. At the regional level, changes in rural land institutions and policy frameworks, particularly the evolution of land tenure systems, adjustments in agricultural subsidies, and reforms in rural land transfer policies, generate diverse incentive structures that influence farmers' land-use decisions (Huang and Yang 2017; Fei *et al.* 2021; Li *et al.* 2021). At the local level, biophysical constraints become especially significant, particularly in China's mountainous regions which comprise 69.1% of the total land area (Han and Song 2019; Lu *et al.* 2022; Li *et al.* 2023). These areas frequently encounter challenges related to terrain conditions, soil quality, and climate variability that fundamentally affect agricultural viability (Li *et al.* 2018; Isbell *et al.* 2019; Li *et al.* 2021; Ma *et al.* 2022). The interaction between these multi-scalar factors, from national demographic shifts to local biophysical conditions, creates complex and spatially differentiated patterns of cropland abandonment.

Despite growing recognition of China's cropland abandonment issue, current understanding remains limited in several aspects. First, existing research has primarily focused on specific regions or short time periods, lacking a comprehensive national-scale analysis of long-term temporal dynamics (Li *et al.* 2021; Ma *et al.* 2022; Zeng *et al.* 2024). Second, while various abandonment types have been identified globally (Potapov *et al.* 2021; Zheng *et al.* 2023), the specific characteristics and transitions of different abandonment patterns in China's diverse geographical contexts remain inadequately understood (Han and Song 2020; Li *et al.* 2021). Third, the relationship between labor migration and cropland abandonment has been examined mainly at local scales (Xu *et al.* 2019), without systematic analysis of migration-abandonment relationships across China's diverse regions. Fourth, although the relationship between land suitability and abandonment has been explored in other countries (Meyfroidt 2016), its implications for China's food security have not been systematically evaluated at the national scale.

This study addresses these gaps by analyzing China's cropland abandonment from 1992 to 2022, encompassing interrelated objectives: (1) quantifying the temporal and spatial evolution of cropland abandonment across scales, (2) characterizing abandonment typologies and their ecological succession processes, (3) analyzing how labor migration influences cropland abandonment through regional threshold effects, and (4) assessing the consequences of land suitability-abandonment relationships on food security. The research employs a methodological framework that integrates long-term land use trajectory analysis, abandonment pattern classification, labor migration impact assessment, and impact assessment of food production.

Accordingly, the remainder of this paper is organized as follows: Section 2 discusses the methodology and data sources used in this study, including identifying cropland abandonment sequences, classifying abandonment patterns, analyzing labor migration effects, and assessing impacts on food production. Section 3 presents detailed findings on trends in cropland abandonment, spatiotemporal patterns, labor migration influences, and impacts on grain production. We discuss the implications of our findings in Section 4, including abandonment stages, regional patterns, migration-abandonment relationships, and policy implications for sustainable agricultural development. Lastly, we conclude with a summary of key findings in Section 5.

2. Methods and data sources

2.1. Methods

Identification and classification of cropland abandonment

We developed a framework to identify abandoned cropland within areas that were consistently classified as stable cropland during 1992–1997. The analysis covers land use trajectories from 1992 to 2022, and the identification consists of three main steps: filtering abnormal fluctuations in land use trajectories, determining annual land use status, and identifying abandonment patterns for each land use trajectory.

(1) Filtering abnormal fluctuations in land use trajectories. A 5-year moving window algorithm was implemented to filter anomalous land use transformations. In this context, "anomalous transformations" denote short-duration land use changes that likely represent classification errors, seasonal variations, or temporary disturbances rather than authentic land use transitions. The algorithm operates on the following principle: when the land use type of a trajectory in a specific year differs from both the previous and subsequent years, it is reclassified to align with the surrounding years to eliminate short-term fluctuations. The 5-year window was selected based on China's characteristic agricultural management cycles, which correspond to the minimum stable period parameters established for cropland (Ts=2 years) and abandonment (Ta=3 years) in the subsequent analysis (Han and Song 2019; Yin *et al.* 2020). The specific filtering rules are as follows:

$$L_f(t)=F(L(t-k:\ t+k)) \tag{1}$$

where $L(t)$ and $L_f(t)$ represent the original and filtered land use trajectories at time t. k is the time window radius, set to 2 in our study, and the filtering rule F is defined as:

$$F(W_t)=\begin{cases}\text{mode}(W_t), & \text{if } L(t)\neq L(t-1) \text{ and } L(t)\neq L(t+1)\\ L(t), & \text{otherwise}\end{cases} \tag{2}$$

where mode(W_t) returns the most frequent land use type within the time window W_t centered at time t. The function identifies potential classification anomalies by comparing each data point to its temporal neighbors. When $L(t)$ differs from the classifications of both adjacent years, the algorithm

substitutes it with the predominant land use type from the surrounding temporal window, maintaining the continuity of actual land use trajectories.

(2) Abandonment status determination. Based on China's agricultural production characteristics of abandoned cropland, three key time parameters were established: the minimum continuous years for stable cropland (Ts=2 years), the minimum continuous years for abandonment (Ta=3 years), and the minimum stable years for recultivation (Tr=2 years) (Li and Song 2021). Initially, for land use status $S(t)$ at time t, the determination focuses on whether it constitutes water or built-up land.

$$\text{State}(t)=\begin{cases}\text{Other land use}, & \text{if } S(t)\in\{4, 5\}\\ f(t), & \text{otherwise}\end{cases} \quad (3)$$

where $f(t)$ is the subsequent determination function used to determine the status of cropland or potential abandonment. For cropland status $S(t)$, the stable cultivated time n is calculated, and for potential abandonment status ($S(t)\in\{2, 3, 6\}$), the non-cropland duration m is calculated, accordingly.

$$n=max\{k:S(t+i)=1,\ i=0, 1, ..., k-1\} \quad (4)$$

The annual classification process follows these criteria:

$$\text{State}(t)=\begin{cases}\text{Stable cropland}, & \text{if } n\geq 2 \text{ and } NoPreAbandon\ (t)\\ \text{Recultivated cropland}, & \text{if } n\geq 2 \text{ and } PreAbandon\ (t)\\ \text{Unstable cropland}, & \text{if } n<2\end{cases} \quad (5)$$

where $NoPreAbandon(t)$ represents a Boolean function that evaluates to true when no abandonment record exists prior to time t in the land use trajectory, and false otherwise. $PreAbandon(t)$ represents a Boolean function that evaluates to true when at least one abandonment event is recorded prior to time t, and false otherwise.

Abandonment status is calculated for potential abandonment status ($S(t)\in\{2, 3, 6\}$) duration m as follows:

$$m=min\{k:S(t-k)=1\} \quad (6)$$

A land parcel's conversion qualifies as valid abandonment when meeting three essential criteria: First, the current land cover must correspond to one of the defined potential abandonment categories (forest, grassland, or unused land). Second, the original land use must have consisted of stable cropland. Third, the conversion process duration must exceed the minimum abandonment threshold (Ta=3 years), thereby distinguishing it from temporary fallowing caused by natural disasters or other short-term disruptions that typically recover within 1–2 growing seasons.

(3) Abandonment pattern classification criteria. The cropland abandonment patterns were categorized according to duration, frequency, and land cover conversion sequences to examine their spatiotemporal characteristics. Three distinct patterns emerged: single long-term abandonment (SL) denotes cropland parcels maintaining non-cropland status for 10 or more consecutive years, representing a sustained transition from agricultural use without recultivation during the study period. Progressive degradation (PD) indicates abandoned cropland parcels undergoing sequential land cover transitions following specific ecological succession pathways: from cropland to forest to grassland to unused land, from cropland to forest to grassland, or from cropland to grassland to unused land. This pattern reflects the gradual ecosystem transformation process after abandonment. Occasional abandonment (OA) comprises cropland parcels experiencing abandonment for 3–9 consecutive years without exhibiting characteristics of either SL or PD patterns.

Spatiotemporal analysis of abandonment dynamics (1) Area-weighted abandonment duration. An analytical method for evaluating cropland abandonment characteristics and patterns in the study area was implemented to examine the duration of land conversions weighted by area. The land conversion type is initially determined based on land use trajectory following abandonment. The formula is expressed as follows (eq. (7)):

$$T_{ij}=\sum_{t=1}^{T} I(L_t=j)\cdot I(L_{t-1}=i) \quad (7)$$

where T_{ij} is the duration of the conversion from land type i to land type j, L_t is the land type at time t, and $I(\cdot)$ is the indicator function that equals 1 when the specified condition is true and 0 otherwise. Thus, $I(L_t=j)$ equals 1 when land at time t is type j, and $I(L_{t-1}=i)$ equals 1 when land at time t–1 is type i. Their product identifies time points of land transition from type i to j, with the summation calculating the total duration.

Secondly, the weighted average duration for each land use type conversion was calculated using the differences in parcel areas (eq. (8)):

$$\overline{T}_j=\frac{\sum_{i=1}^{N} A_j\cdot T_{ij}}{\sum_{i=1}^{N} A_j\cdot I(T_{ij}>0)} \quad (8)$$

where $\overline{T}_j$ is the area-weighted average duration of land use type j; A_i is the parcel area corresponding to trajectory, N is the total number of trajectories in the region. An area with a higher $\overline{T}_j$ for forest land indicates that abandoned cropland in that region mainly transforms into forest land and is abandoned over a longer period; an area with a lower $\overline{T}_j$ indicates staged cropland abandonment.

(2) Gravity center analysis for spatial migration patterns. To analyze the spatial migration patterns of cropland abandonment, the gravity center was calculated for five consecutive five-year periods (1998–2002, 2003–2007, 2008–2012, 2013–2017, and 2018–2022). The gravity center represents the weighted central point of cropland abandonment distribution across geographical space, with each county's coordinates weighted by its abandonment rate. This methodology quantifies the central tendency of abandonment intensity distribution and enables tracking its migration over time, revealing spatial shifts in cropland abandonment concentration.

Quantifying labor migration effects on abandonment To examine the relationship between labor migration and cropland abandonment, a panel dataset was constructed spanning 2006–2022 for 30 provincial-level administrative regions in China. Migration data were obtained from the National Bureau of Statistics' annual rural household surveys, while abandonment data were derived from the annual identification of abandoned cropland (2006–2022) with a 300-m spatial resolution.

We constructed three categories of migration variables to capture different dimensions of labor mobility. Migration structure variables quantified the temporal characteristics of

migration patterns, including long-term migration ratio ($LTM_{i,t}$) representing the proportion of migrant workers staying away for more than 6 months annually. Spatial distance variables measured geographical aspects of migration, comprising within-county migration ratio ($WCM_{i,t}$), within-province migration ratio ($WPM_{i,t}$), and interprovincial migration ratio ($IPM_{i,t}$), each calculated as the proportion of migrants moving to respective destinations relative to total labor force. Migration dynamic variables assessed temporal changes in migration patterns, including migration change rate ($MCR_{i,t}=M_{i,t}-M_{i,t-1}$), return migration rate ($RMR_{i,t}=max[MCR_{i,t}, 0]$), and outflow rate ($OFR_{i,t}=max[-MCR_{i,t}, 0]$). Missing values in the dataset (less than 2.5%) were imputed using province-specific means to maintain analytical consistency. All ratio variables were standardized to percentages for interpretation consistency and comparability across regions.

Fixed-effects panel regression models were employed to examine the relationship between labor migration and cropland abandonment, accounting for unobserved province-specific characteristics while preserving the ability to analyze spatiotemporal heterogeneity. All migration variables were incorporated with a three-year lag (t–3), aligning with the operational definition of cropland abandonment requiring a minimum of three consecutive years of non-cultivation (Ta=3 years). This temporal specification acknowledges the delayed manifestation of abandonment following migration events and aligns with previous empirical studies on labor outmigration and land use transitions (Han and Song 2019, 2020). The baseline specification is expressed as (eq. (9)):

$$AR_{i,t}=\beta_0+\beta_1 LTM_{i,t-3}+\beta_2 LTM^2_{i,t-3}+\beta_3 WCM_{i,t-3}+\beta_4 WPM_{i,t-3}+\beta_5 IPM_{i,t-3}+\beta_6 RMR_{i,t-3}+\beta_7 OFR_{i,t-3}+\beta_8 X_{i,t-3}+\mu_i+\lambda_t+\varepsilon_{i,t} \quad (9)$$

where $AR_{i,t}$ represents the cropland abandonment rate for province i in year t; $LTM_{i,t-3}$ and $LTM^2_{i,t-3}$ are the lagged linear and quadratic terms of long-term migration ratio to capture potential non-linear effects; $WCM_{i,t-3}$, $WPM_{i,t-3}$, and $IPM_{i,t-3}$ are lagged spatial distance migration variables; $RMR_{i,t-3}$ and $OFR_{i,t-3}$ are lagged return and outflow rates; $X_{i,t-3}$ is a vector of control variables including land transfer rate, primary industry employment ratio, terrain slope index, disaster-affected area, agricultural technology contribution, grain yield, and agricultural machinery power; μ_i and λ_t denote province and year fixed effects; and $\varepsilon_{i,t}$ is the error term. The Hausman test confirmed the appropriateness of fixed effects over random effects specification (χ^2=47.28, P<0.01). We calculated robust standard errors clustered at the provincial level to address potential heteroskedasticity and serial correlation.

To examine spatial heterogeneity, the analysis was stratified by geographical regions (eastern, central, western, and northeastern region of China) according to China's standard administrative division. Eq. (10) was estimated separately for each region to allow coefficients to vary regionally. Furthermore, panel threshold regression analysis was implemented to identify critical inflection points in the relationship between long-term migration ratio and abandonment rates. The model follows the form (eq. (10)):

$$\begin{cases} AR_{i,t}=\alpha_1+\beta_1 LTM_{i,t}+\theta_1 X_{i,t}+\mu_i+\lambda_t+\varepsilon_{i,t}, \text{ if } LTM_{i,t}\le\gamma \\ AR_{i,t}=\alpha_2+\beta_2 LTM_{i,t}+\theta_2 X_{i,t}+\mu_i+\lambda_t+\varepsilon_{i,t}, \text{ if } LTM_{i,t}>\gamma \end{cases} \quad (10)$$

where γ denotes the threshold value to be estimated, and other variables retain their previous definitions. The optimal threshold for each region was determined by minimizing the residual sum of squares across potential threshold values through a grid search procedure spanning the 10th to 90th percentiles of the migration distribution, with increments of 0.01. The statistical significance of identified thresholds was established using the bootstrap method with 1,000 replications.

Food security impact assessment The assessment of abandoned cropland's potential impact on food security considered two dimensions: cultivability suitability and grain production capacity. For cultivability suitability analysis, China's eight-level land suitability classification system was utilized to identify the cultivability suitability of abandoned parcels. Levels 1–4 were classified as cultivability suitable and levels 5–8 as unsuitable for agricultural land use. The suitability of abandoned parcels was determined by overlaying the spatial distribution of abandoned land with the land suitability classification results for each year.

For grain production loss assessment, both potential and actual grain production losses were quantified. Baseline productivity values were derived from two datasets. Potential yields were derived from the Global Agro-Ecological Zones (GAEZ) model for 2000, representing theoretical maximum productivity. Actual yields were sourced from SPAM 2000 dataset, representing historical production patterns. This dataset encompasses the five major crops (wheat, rice, maize, soybean, and sweet potato) that constitute approximately 97.7% of China's grain production. Parcel-level production losses were calculated by multiplying each abandoned area by its corresponding yield values (eqs. (11) and (12)):

$$L_p=A\times Y_p \quad (11)$$

$$L_a=A\times Y_a \quad (12)$$

where L_p and L_a represent the potential and actual production loss (kg), respectively. A denotes the area of the abandoned parcel (ha), Y_p indicates the potential yield from GAEZ (kg ha^{-1}), and Y_a represents the actual yield derived from SPAM (kg ha^{-1}).

The grain production losses were disaggregated according to land suitability using (eqs. (13) to (16)):

$$L_{s,p}=\sum_{i=1}^{n} L_{p,i}\times S_i \quad (13)$$

$$L_{u,p}=\sum_{i=1}^{n} L_{p,i}\times(1-S_i) \quad (14)$$

$$L_{s,a}=\sum_{i=1}^{n} L_{a,i}\times S_i \quad (15)$$

$$L_{u,a}=\sum_{i=1}^{n} L_{a,i}\times(1-S_i) \quad (16)$$

where $L_{s,p}$ and $L_{u,p}$ represent potential grain production losses on suitable and unsuitable land respectively; $L_{s,a}$ and $L_{u,a}$ represent actual grain production losses on suitable and unsuitable land respectively; i denotes the abandoned parcel, n is the total number of abandoned parcels, and S_i is the suitability indicator (1 for suitable, 0 for unsuitable).

2.2. Data sources and preprocessing

This study utilized five primary datasets to analyze cropland abandonment in China. The European Space Agency Climate Change Initiative (ESA CCI) land cover dataset (1992–2022) served as the foundation for land use change analysis. This dataset provides global land cover information

at 300-m spatial resolution, derived from remote sensing images captured by the MERIS instrument aboard the European Space Agency Environmental Satellite and the Sentinel satellite series (Plummer *et al.* 2017).

The China land suitability classification map was employed to assess agricultural capability using an eight-level classification system at 1 km spatial resolution (Shi 1982). This classification categorizes land as: suitable cropland (code 1), suitable for agriculture, forestry and pasture (code 2), suitable for agriculture and forestry (code 3), suitable for agriculture and pasture (code 4), suitable for forestry and pasture (code 5), suitable for forestry (code 6), suitable for pasture (code 7), and unsuitable for agriculture, forestry or pasture (code 8).

To evaluate agricultural productivity, we incorporated the China Cropland Production Potential dataset (2000) (Liu *et al.* 2015), which quantifies maximum grain production potential while considering diverse cropping systems (including double cropping in one year, triple cropping in two years, and triple cropping in one year). This dataset provides measurements in kg ha^{-1} at 1 km spatial resolution and was developed using the GAEZ model. For actual production metrics, we utilized the SPAM 2000 v3.0.7 Global Data (IFPRI, 2019), which provides spatially disaggregated crop production statistics.

For examining labor migration effects on cropland abandonment, we compiled panel data from various official statistical sources spanning 2006–2022, including the *China Rural Statistical Yearbook* (NBSC 2006–2022), *China Rural Operation and Management Statistical Annual Report* (MARA 2006–2018), and *China Rural Policy and Reform Statistical Annual Report* (MARA 2019–2022). These sources provided comprehensive information on rural labor dynamics across China's 30 provincial-level administrative regions, documenting migration patterns by duration (long-term *vs.* short-term) and distance (within-county, within-province, and interprovincial). Missing values in the migration dataset (less than 2.5%) were imputed using province-specific means to maintain analytical consistency.

Data preprocessing involved four sequential steps to ensure spatial consistency across all datasets. First, we projected the ESA CCI land cover data to the Albers Equal Area projection system to establish a standardized spatial reference framework. Second, we established correspondence between land use and land cover classifications (Table 1) and reclassified China's land cover into six categories: cropland, forest land, grassland, water bodies, built-up land, and unused land. In this classification scheme, forest land, grassland, and unused land (codes 2, 3, 6) were designated as valid abandonment conversion types. Third, we resampled the land suitability classification map and cropland production potential data to match the spatial resolution of the reclassified land use data. Fourth, we created a unified spatial database to ensure consistency of all datasets in terms of spatial reference system and resolution.

Table 1 Correspondence between land use types and ESA land cover classification[1)]

Land use type	Land use code	ESA land cover (land cover code)
Cropland	1	Irrigated cropland, rainfed cropland, mosaic cropland (10, 20, 30)
Forest	2	Tree cover (evergreen/deciduous, broadleaved/needleleaved), shrubland, mosaic vegetation (40, 50, 60–62, 70–72, 80–82, 90, 100, 120–122, 160, 170)
Grassland	3	Grassland, mosaic herbaceous cover, lichens/mosses, sparse vegetation (110, 130, 140, 150–153)
Water bodies	4	Water bodies, permanent snow/ice, wetland (46, 210, 220)
Built-up land	5	Urban and rural settlements, industrial areas (190)
Unused land	6	Bare areas, sandy areas, saline-alkali land, marsh, bare rock (200–202)

[1)] Land use codes represent the six major categories established in this study; ESA codes represent the European Space Agency's land cover classification system.

3. Results

3.1. Spatiotemporal characteristics of cropland abandonment

Temporal dynamics of cropland abandonment Analysis of China's annual land use trajectory revealed the dynamics of cropland use and abandonment. The findings indicate that China's stable cropland area reached 229.1×10^4 km^2 between 1992 and 1997 (Fig. 1). Due to urban expansion and cropland abandonment, the stable cropland area decreased steadily over 25 years, reaching 212.7×10^4 km^2 in 2022 (a net reduction of 7.16%), with abandonment-induced loss accounting for 3.01% of all stable cropland during this period. China's cropland abandonment increased in distinct temporal phases. The period from 1998 to 2002 showed slow growth, with an average annual abandonment area of 2.1×10^4 km^2, approximately 0.91% of stable cropland. From 2003 to 2009, the cropland abandonment rate increased rapidly from 1.39% to 3.81%, representing an average increase of 0.35 percentage points annually. Between 2010 and 2016, the abandoned area continued to expand, reaching a historical peak of 8.5×10^4 km^2 in 2016, with an abandonment rate of 3.98%. After 2016, the abandonment rate declined from 3.98% to 3.01% in 2022.

Spatial patterns and typology of cropland abandonment The initial abandonment timing exhibited a "three-peak, two-valley" pattern during 1998–2022 (Fig. 2). The first peak occurred in 1998 (1.18×10^4 km^2), the second in 2002 (approximately 1.35×10^4 km^2), and the third in 2010 (1.02×10^4 km^2) (Fig. 2-B). The 2002 peak reached the highest value over the 20-year period, exceeding the 1998 level by 14.4%. The valleys emerged in 2000 (approximately 0.20×10^4 km^2) and 2008 (approximately 0.15×10^4 km^2). After 2014, first-time abandonments decreased markedly, with the initial abandonment area remaining below 0.15×10^4 km^2. Regional differences in abandonment durations were significant (Fig. 2-A). The phenomenon commonly persisted for five to ten years in southwest mountainous areas of Yunnan, Guizhou, and Sichuan provinces, while most eastern coastal and central plain counties experienced abandonment durations of less than one year.

The analysis evaluated three abandonment patterns:

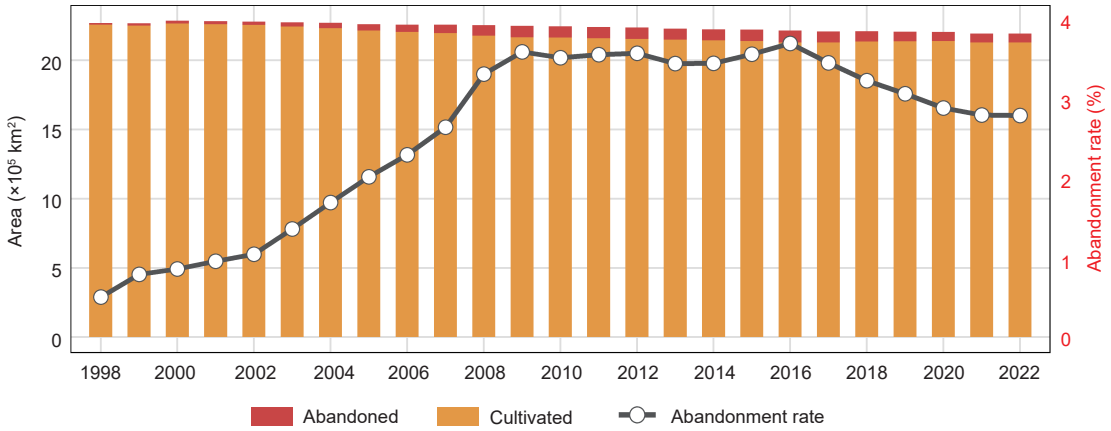
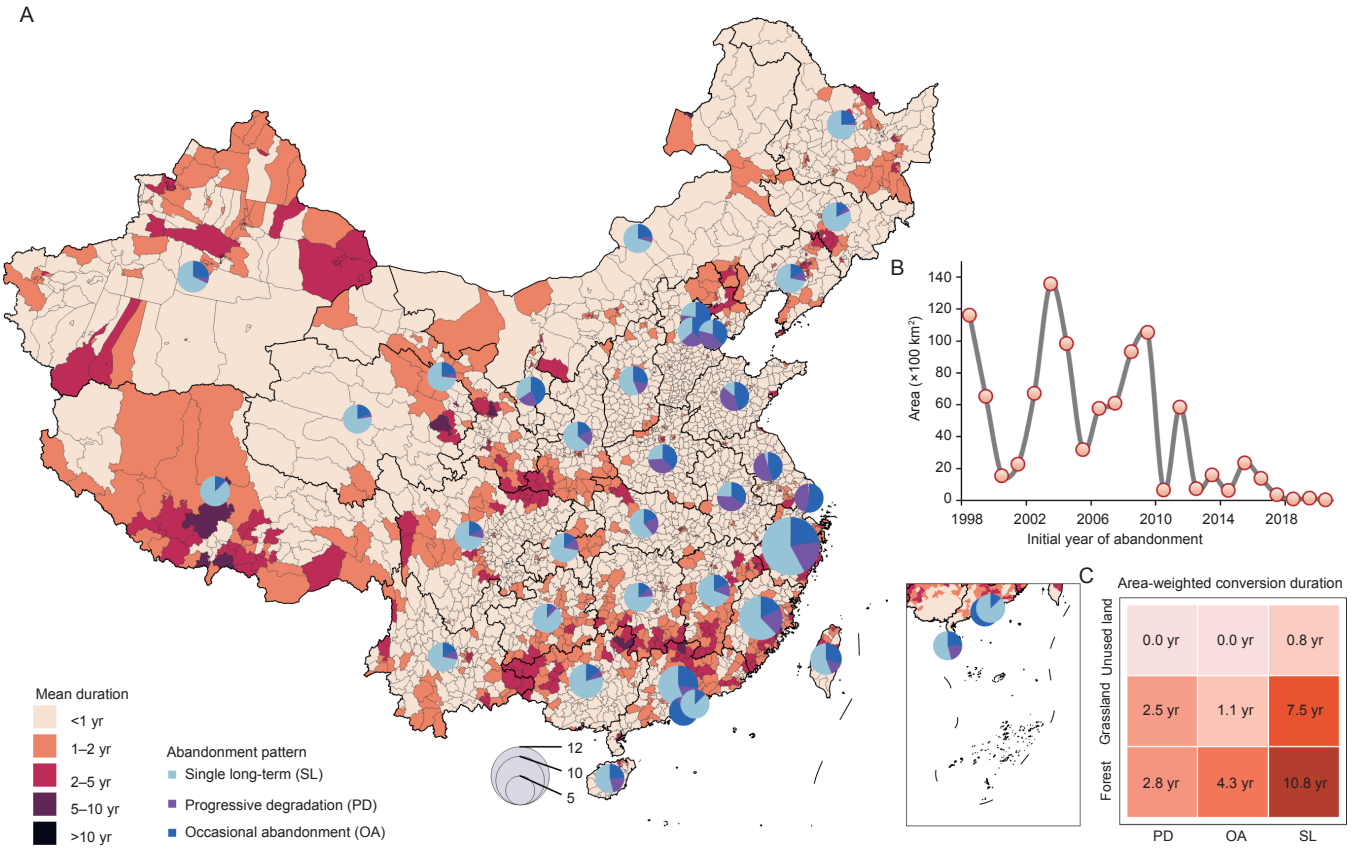


Fig. 1 Dynamics of cropland area and abandonment rate in China (1998–2022).



审图号：GS 京 (2026) 0720 号

Fig. 2 Spatiotemporal characteristics and typology of cropland abandonment in China (1998–2022). A, spatial distribution of abandonment duration at county level and provincial-scale abandonment patterns (pie chart size indicates abandonment rate, pie chart composition represents the proportion of progressive degradation (PD), occasional abandonment (OA), and single long-term (SL)). B, annual dynamics of initial cropland abandonment area (×10² km²). C, area-weighted land conversion duration (yr) under different abandonment patterns.

single long-term (≥10 years), progressive degradation, and occasional abandonment (3–9 years) (Fig. 2-C). The findings revealed that single long-term abandonment exhibited the longest duration (10.8 years) when converted to forest land, followed by conversion to grassland (7.5 years), while conversion to unused land showed the shortest duration (0.8 years). Consequently, long-term abandoned plots typically underwent complete ecosystem succession. For occasional abandonment, forest land conversion required 4.3 years, grassland conversion took 1.1 years, and virtually no conversion to unused land occurred, indicating timely intervention and management. In the progressive degradation

pattern, conversion durations to forest and grassland were 2.8 and 2.5 years, respectively, suggesting gradual land use transformation. At the provincial level, regions demonstrated distinct pattern characteristics. Eastern coastal provinces predominantly exhibited occasional abandonment, attributed to economic development and frequent land use conversions. Mountainous counties in southwestern provinces exhibited high percentages of long-term abandonment and progressive degradation, reflecting mountain agriculture vulnerability and natural ecosystem recovery.

Spatiotemporal heterogeneity of cropland abandonment The spatiotemporal analysis of China's cropland abandonment from 1998 to 2022, conducted using standardized 5-year intervals, revealed distinct regional patterns. At the provincial level, the national cropland abandonment ratio increased from 0.80% in 1998–2002 to 6.14% in 2013–2017, representing a 5.34 percentage point increase. Southwestern China's provincial-level administrative regions, particularly Yunnan, Sichuan, and Chongqing, exhibited consistently increasing abandonment rates. The Mann-Kendall trend test indicated significantly higher growth rates in southwestern provinces than in other regions (τ=0.62, P<0.05). Notably, Yunnan experienced the most substantial increase across all five periods, with rates rising from 1.43% in 1998–2002 to 5.91% in 2018–2022, supported by Mann-Kendall trend analysis showing a significant temporal trend (τ=0.73, P<0.01). Conversely, eastern coastal provinces (Jiangsu, Zhejiang, and Anhui) and central and southeastern provinces (Guangdong, Fujian, Jiangxi, Hubei, and Hunan) maintained relatively low and stable abandonment rates, generally below 5% throughout the study period. Specifically, Jiangxi, Anhui, and Hubei provinces maintained abandonment rates of approximately 3% over the years.

County-level analysis revealed distinctive spatial clustering patterns and a clear gravitational center migration trend (Fig. 3-A–E). During 1998–2002, high-intensity abandonment (>15%) predominantly occurred in marginal mountainous areas, specifically the Altay region in northern Xinjiang and the Greater Khingan Range area in northeastern Heilongjiang (Fig. 3-A). Post 2003–2007, these high-intensity abandonment areas in the Northeast expanded from isolated mountainous regions to extensive parts of northern Heilongjiang (Fig. 3-B). Concurrently, abandonment issues intensified in the southwest, with Sichuan's affected areas expanding from western plateau regions to eastern mountainous areas, while Yunnan's affected areas spread from the northeast to the south (Fig. 3-C and D). By 2018–2022, substantial high-intensity abandonment emerged in northeastern Inner Mongolia and southeastern Xizang (Fig. 3-E). Throughout the study period, traditional agricultural areas in the North China Plain and the middle and lower reaches of the Yangtze River Plain maintained low abandonment rates below 5%. Analysis of gravitational center migration from 1998–2022 indicated a consistent northeast-to-southwest movement spanning approximately 1,000 km, characterized by rapid movement during 2002–2010 followed by stabilization (Fig. 3-F). This trajectory reflects the shifting focus of abandonment from northeastern state farms to southwestern mountainous regions, corresponding with regional socioeconomic transitions.

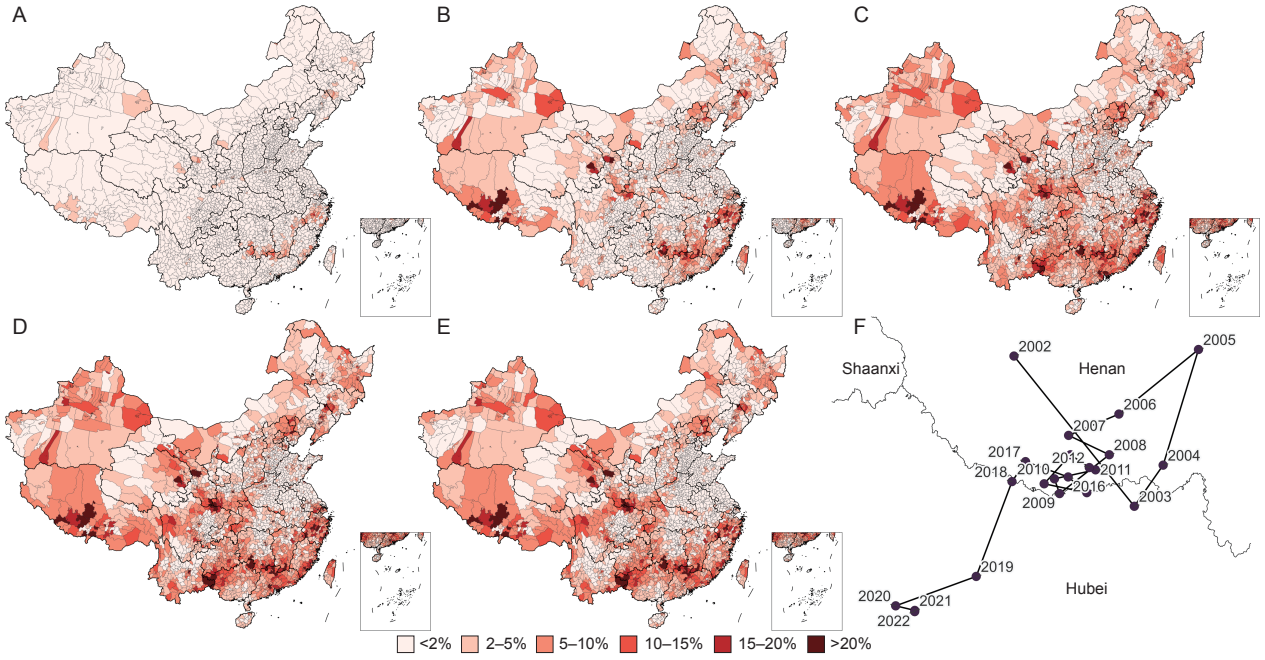
3.2. Labor migration impacts on cropland abandonment

Migration-abandonment relationship Panel regression analysis revealed a significant non-linear relationship between long-term migration ratio (LTM, lagged by 3 years) and cropland abandonment rate (Table 2). The first-order term coefficient demonstrated significant negative correlation (β=–0.149, P<0.01), while the second-order term coefficient showed a significant positive correlation (β=0.001, P<0.01). These findings are consistent with the moderate migration hypothesis, wherein moderate levels of long-term migration reduce abandonment rates through increased non-agricultural income facilitating land transfer or hired labor, while excessive long-term migration leads to agricultural labor shortages beyond market compensation mechanisms, thereby increasing abandonment.

The spatial distance of labor migration exhibited differentiated effects on abandonment rates. Within-county migration (WCM) significantly reduced abandonment rates (β=–0.005, P<0.01), whereas within-province migration (WPM) significantly increased abandonment rates (β=0.008, P<0.01). These findings indicate that short-distance migration enables households to balance non-agricultural employment with agricultural production, while medium-distance migration creates conditions where farmers can neither effectively maintain agricultural activities nor accumulate sufficient resources to support land transfer. Interprovincial migration (IPM) showed a negative but non-significant coefficient (β=–0.001, P>0.10), potentially reflecting dual effects: increasing labor shortage risks while generating higher non-agricultural income to support land transfer or hired labor.

The return migration rate (RMR, lagged by 3 years) had a significant positive effect on the abandonment rate (β=0.038, P<0.01), indicating that returning farmers face diminished agricultural skills and insufficient capital accumulation, hindering their immediate effective participation in agricultural production. Among control variables, disaster-affected area showed a significant positive effect (β=1.931, P<0.01), while agricultural technology contribution (β=–0.002, P<0.01), grain yield (β=–0.065, P<0.01), and agricultural machinery power (β=–2.445, P<0.01) exhibited significant negative effects on abandonment rates.

Regional heterogeneity in migration effects Regional stratification analysis revealed substantial spatial heterogeneity in the effects of labor migration on cropland abandonment (Table 3). In eastern regions, the long-term migration ratio demonstrated a significant negative correlation with abandonment rate (β=–2.519, P<0.05), aligning with the moderate migration hypothesis. However, all spatial distance migration variables in eastern regions exhibited positive correlations with abandonment, indicating that overall labor outflow increases abandonment risk. Specifically, within-county migration (β=2.417, P<0.01), within-province migration (β=2.454, P<0.01), and interprovincial migration (β=2.332, P<0.01) all displayed significant positive effects on abandonment rates.



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Fig. 3 Spatiotemporal patterns of cropland abandonment rate at county level in China. A, 1998–2002. B, 2003–2007. C, 2008–2012. D, 2013–2017. E, 2018–2022. F, trajectory of the gravity center.

Table 2 Migration effects on cropland abandonment

Variable[1)]	Coefficients
Intercept	10.968** (1.700)
LTM (*t*–3) (%)	–0.149** (0.036)
LTM squared (*t*–3)	0.001** (0.000)
WCM (*t*–3)	–0.005** (0.002)
WPM (*t*–3)	0.008** (0.002)
IPM (*t*–3)	–0.001 (0.001)
RMR (*t*–3) (%)	0.038** (0.009)
Outflow migration rate (*t*–3) (%)	0.005 (0.009)
Land transfer rate (*t*–3) (%)	–0.000 (0.000)
Primary industry employment (*t*–3) (%)	0.003 (0.008)
Terrain slope index	0.028 (0.141)
Disaster-affected area (*t*–3) (×10³ ha)	1.931** (0.659)
Agricultural technology contribution (*t*–3)	–0.002** (0.001)
Grain yield (*t*–3) (t ha⁻¹)	–0.065** (0.016)
Agricultural machinery power (*t*–3)	–2.445** (1.209)
R^2	0.399
Adj. R^2	0.378
Num. obs.	420

[1)] LTM, long-term migration ratio; WCM, within-county migration; WPM, within-province migration; IPM, interprovincial migration; RMR, return migration rate.
Robust standard errors in parentheses. *, P<0.1; **, P<0.05; ***, P<0.01.

The northeastern region demonstrated a characteristic U-shaped relationship, with the long-term migration ratio negatively correlated with abandonment (β=–1.645, P<0.05) and its squared term significantly positive (β=0.010, P<0.01). This pattern reflects the beneficial role of moderate labor transfer under the region's large-scale farming model, while agricultural machinery power showed a substantial negative effect (β=–162.214, P<0.05), highlighting the significance of mechanization in this region.

In central regions, abandonment was predominantly influenced by institutional factors, with land transfer rate exhibiting a significant negative effect (β=–0.000, P<0.01). The advancement of mechanization (agricultural machinery power: β=61.578, P<0.01) may accelerate the abandonment of plots unsuitable for mechanical operations in this region.

Western regions exhibited a significant negative correlation between labor outflow rate and abandonment rate (β=–0.156, P<0.01), indicating that within the region's small-scale dispersed agricultural structure, labor outflow facilitates systematic withdrawal of marginal land and intensive development of core agricultural areas. Primary industry employment demonstrated a significant positive effect (β=0.118, P<0.01) in this region.

Threshold effects of labor migration across regions Panel threshold regression analysis revealed distinct non-linear relationships between long-term labor migration and cropland abandonment across China's regions (Fig. 4). The identified thresholds: eastern (7.24%), western (9.58%), northeastern (13.93%), and central (37.08%), represent critical points where the impact of labor outflows on abandonment fundamentally shifts.

The eastern and central regions exhibited positive migration-abandonment relationships across their thresholds, albeit with varying sensitivities. In eastern regions, the relationship maintained strong positive correlations both below threshold (β=0.711) and above it (β=0.640), aligning with findings of significant abandonment pressures from labor outflows (Table 3). This persistent effect, despite high mechanization levels, indicates structural constraints in

substituting labor with technology in eastern China's complex agricultural landscapes. Central regions demonstrated resilience to labor outflows, showing minimal effects below their high threshold (β=0.027) and moderate effects above it (β=0.275). This resilience corresponds with observations that central regions benefit substantially from land transfer markets (land transfer rate: β=–0.000, P<0.01, Table 3), which effectively redistribute agricultural resources during labor scarcity.

The western and northeast regions demonstrated threshold-dependent reversals in abandonment effects. Below their respective thresholds, both regions exhibited negative relationships (western: β=–0.460; northeastern: β=–0.261), suggesting that moderate labor outflows reduced abandonment rates. When migration exceeded these thresholds, the relationships shifted toward neutral (western:

Table 3 Regional heterogeneity in migration-abandonment relationship

Variable[1)]	Eastern	Central	Western	Northeastern
LTM (*t*–3)	–2.519** (0.576)	9.486 (5.563)	0.318 (4.973)	–1.645** (0.366)
LTM squared (*t*–3)	0.001 (0.001)	0.001 (0.002)	–0.000 (0.001)	0.010*** (0.002)
WCM (*t*–3)	2.417** (0.553)	–9.707 (5.551)	–0.316 (4.983)	0.176 (0.092)
WPM (*t*–3)	2.454** (0.568)	–9.532 (5.505)	–0.511 (4.994)	0.142 (0.098)
IPM (*t*–3)	2.332** (0.556)	–9.614 (5.537)	–0.324 (4.985)	0.063 (0.093)
RMR (*t*–3)	0.059*** (0.010)	0.034 (0.047)	–0.012 (0.016)	–0.467 (0.090)
Outflow migration rate (*t*–3)	–0.008 (0.035)	0.008 (0.015)	–0.156*** (0.075)	–0.002 (0.014)
Land transfer rate (*t*–3)	0.000 (0.000)	–0.000*** (0.000)	–0.000*** (0.000)	0.000 (0.000)
Primary industry employment (*t*–3)	0.010 (0.027)	–0.002 (0.037)	0.118*** (0.014)	–0.017 (0.047)
Terrain slope index	1.112*** (0.294)	1.477*** (0.086)	0.055 (0.078)	–34.446** (12.369)
Disaster-affected area (*t*–3) (×10^3 ha)	3.892*** (1.839)	13.128*** (1.877)	–2.749*** (0.581)	–5.181 (1.122)
Grain yield (*t*–3) (t ha^{-1})	0.943*** (0.399)	0.294*** (0.116)	0.259*** (0.067)	13.814** (5.338)
Agricultural machinery power (*t*–3)	0.366 (0.820)	61.578*** (14.773)	–3.887*** (0.888)	–162.214** (77.406)
R^2	0.940	0.989	0.856	0.956
Adjusted R^2	0.926	0.984	0.827	0.881
Number of observations	140	84	154	42

[1)] LTM, long-term migration ratio; WCM, within-county migration; WPM, within-province migration; IPM, interprovincial migration; RMR, return migration rate.
Robust standard errors in parentheses. *, P<0.1; **, P<0.05; ***, P<0.01.

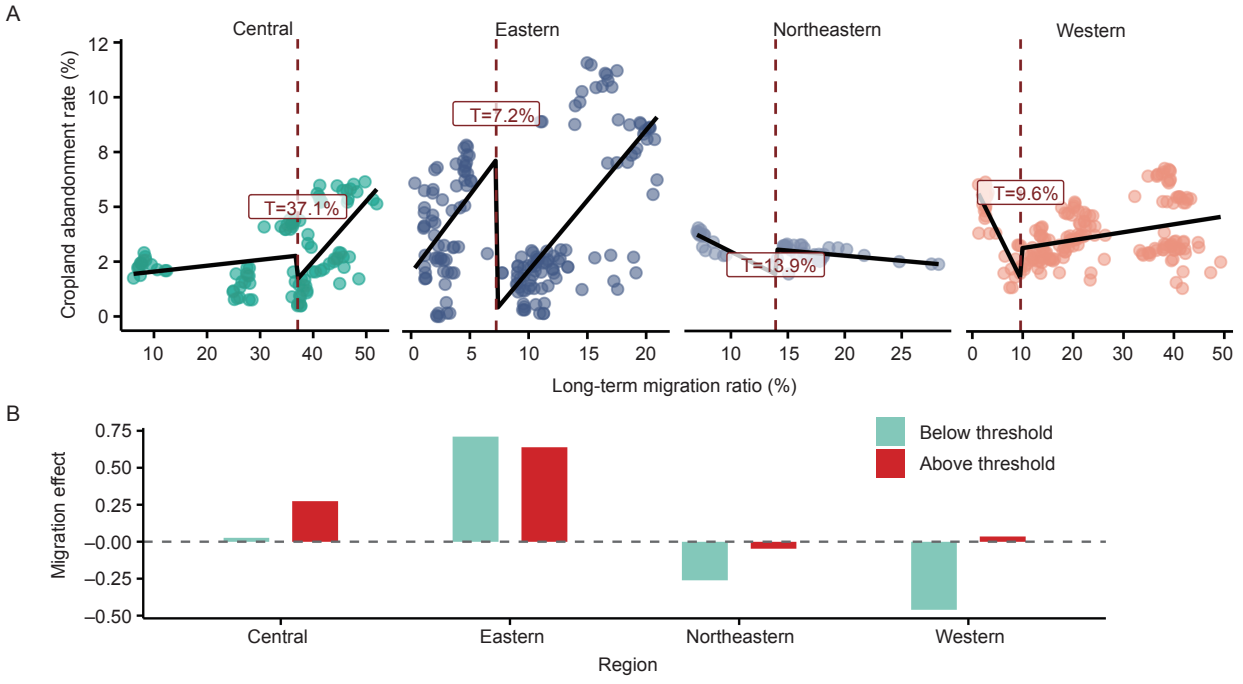


Fig. 4 Regional threshold effects of long-term migration on cropland abandonment rates. A, threshold of long-term migration ratio and abandonment rate by region. Dots represent observations, black solid lines show fitted curves, red dashed lines indicate optimal thresholds, and T values show threshold percentages. B, comparison of marginal effects of migration on abandonment before and after thresholds. Green bars represent effect coefficients below threshold, red bars show effect coefficients above threshold, and horizontal dashed line indicates zero-effect baseline. Positive values indicate promotion of abandonment, while negative values indicate suppression.

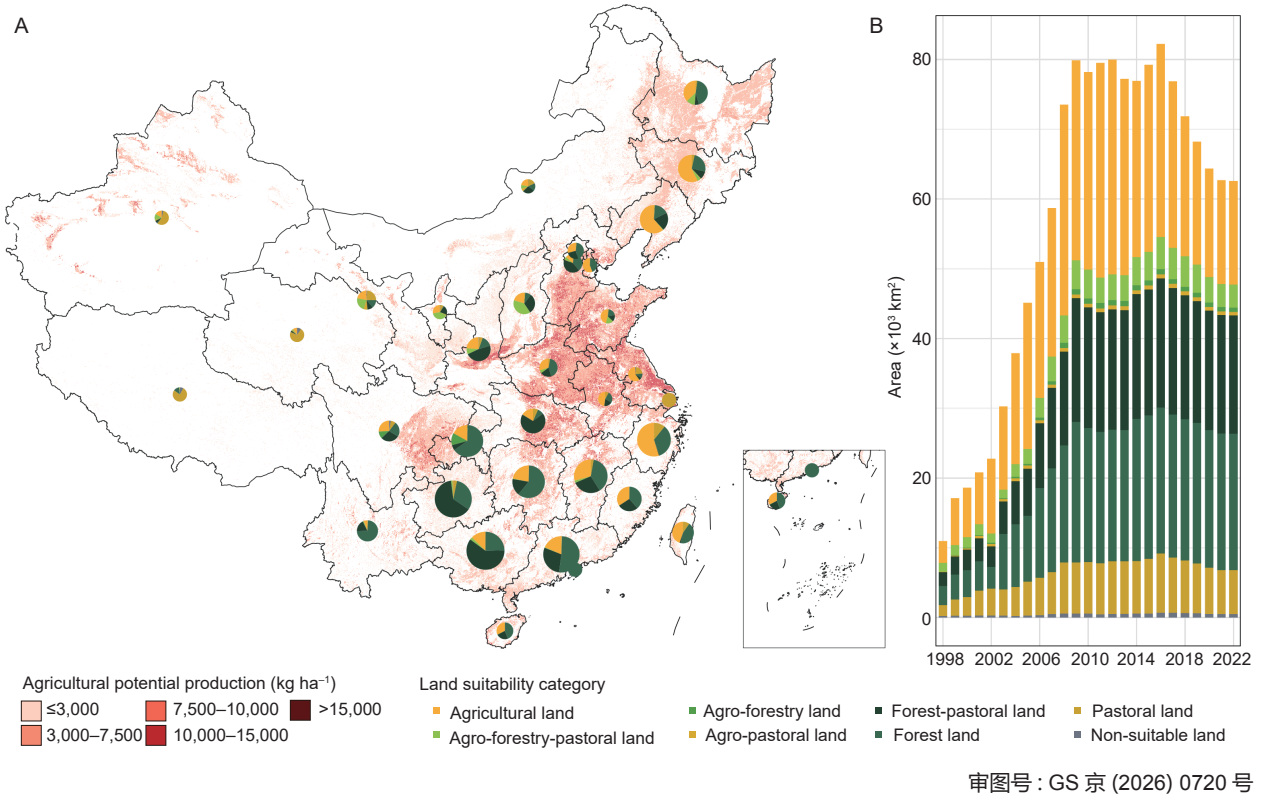
β=0.036; northeastern: β=–0.047). This pattern in western regions supports the finding of negative association between outflow rates and abandonment (β=–0.156, P<0.01, Table 3), illustrating how moderate labor transfers optimize agricultural resource allocation through abandonment of marginal lands and intensification of farming on higher-quality parcels. The Northeast's transition from strong negative to weak negative effects at its threshold reflects diminishing returns of labor outflows in a region characterized by large-scale, mechanized farming systems, where agricultural machinery significantly influences abandonment dynamics (agricultural machinery power: β=–162.214, P<0.05, Table 3).

3.3. Food security implications of cropland abandonment

Agricultural suitability composition of abandoned cropland According to China's land cultivability suitability classification system, high cultivation suitability plots encompass four categories: agricultural land, agro-forestry-pastoral land, agro-forestry land, and agro-pastoral land. Low cultivation suitability plots include forest-pastoral land, forest land, pastoral land, and unsuitable land. Analysis from 1998 to 2022 indicates that 42.50% of annually abandoned cropland occurred on high cultivation suitability plots, though this proportion decreased from 2003 to 2022 (Fig. 5). Conversely, 57.50% of abandoned cropland was found on low cultivation suitability plots, with this area exhibiting an annual increasing trend (average annual increase of 0.34%) from 1998 to 2016, followed by a slight decrease during 2017–2022. Additionally, mixed agricultural function areas constituted 28.04% annual abandonment on average.

Spatially, cropland abandonment demonstrated a significant negative correlation with agricultural suitability. The dominant suitable land types in abandoned areas revealed clear regional patterns of "agricultural east, pastoral west" and "forest south, agricultural north." In eastern regions, abandonment primarily occurred on plots dominated by suitable agricultural land. For example, in 2022, provinces including Jiangsu (60.00%), Liaoning (61.03%), and Zhejiang (54.81%) exhibited over 50% of their abandoned cropland on suitable agricultural land. In central regions, abandonment predominantly occurred on "agro-forest mixed" plots. For example, Hubei Province reported abandonment on forest-suitable land at 68.87%. In western regions, abandoned plots were primarily distributed on pastoral-suitable land, with Qinghai and Xizang showing pastoral land proportions of 72.23 and 77.14%, respectively.

Assessment of grain production loss Analysis of abandoned cropland from 1998 to 2022 revealed an inverted U-shaped pattern in grain production losses, with both potential and actual losses peaking during 2010–2012 before declining through 2022 (Fig. 6-A). Potential grain losses reached maximum values of 15.0 and 8.8 million tonnes for low and high suitability land respectively in 2010, while actual losses (based on SPAM data) peaked at 7.8 million tonnes for low suitability land (2010) and 4.6 million tonnes for high suitability land (2012). The gap between potential and actual



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Fig. 5 Spatial-temporal patterns of land suitability composition in abandoned farmland across China (1992–2022). A, provincial distribution of land suitability categories in abandoned farmland (pie charts) overlaid on agricultural potential production of stable cropland (background) in 2022. B, temporal changes in land suitability composition of abandoned farmland at national scale.

losses remained consistent (actual/potential ratio: 0.52 for low suitability, 0.53 for high suitability), while the narrowing difference between high and low suitability actual grain losses during 2018–2022 suggests a transition toward abandonment of genuinely marginal rather than high-productivity agricultural land in recent years.

Rice dominated the crop-specific production losses, representing 54.0% of total actual grain loss during the study period, followed by maize (22.9%), wheat (15.4%), sweet potato (7.1%), and soybean (0.6%) (Fig. 6-B). The concentration of losses in staple grains (rice, maize, and wheat collectively accounting for 92.3% of production impact) has substantial implications for food security, particularly as peak losses for these crops occurred during 2011–2012, coinciding with China's high-level abandonment phase. The consistent proportional distribution of crop-specific losses throughout the study period indicates that abandonment affected different cropping systems in proportion to their spatial distribution rather than targeting specific crops selectively.

The regional distribution of grain production losses demonstrated persistent spatial heterogeneity, with the Middle-Lower Yangtze region contributing the largest share, though decreasing from 35% (1998) to 25% (2022), while the North China Plain maintained a stable 20–25% contribution (Fig. 6-C). The northeastern region showed the most pronounced temporal variation (increasing from 20 to 30% during 2002–2006 before declining to 15–20% by 2022), while South China, Northwest, and Southwest regions collectively comprised 30–35% of total grain loss. These patterns reflect region-specific interactions between biophysical constraints, socioeconomic factors, and policy environments, with the temporal stability of regional contributions after 2010 indicating that established regional determinants of abandonment have persisted despite national-level policy interventions.

4. Discussion

4.1. Spatiotemporal evolution and driving mechanisms of cropland abandonment

Our research reveals the spatiotemporal evolution of China's cropland abandonment from 1998 to 2022, identifying four distinct phases: slow growth, rapid increase, high-level fluctuation, and gradual decline. This finding is consistent with previous studies reporting an overall upward trend in China's cropland abandonment, though with variations across different periods (Han and Song 2020; Guo *et al.* 2023; Tu *et al.* 2024). Our analysis characterizes each phase quantitatively: from 1998 to 2002, cropland abandonment increased slowly at an annual rate of 0.21×10^5 km^2; from 2003 to 2009, it rose rapidly with an average annual increase of 0.35 percentage points; from 2010 to 2016, it maintained high-level fluctuations, reaching a peak of 3.98% in 2016, before gradually declining to 3.01% by 2022 (Yin *et al.* 2020; Yu *et al.* 2021). This phasic pattern demonstrates the dynamic rather than linear trend of abandonment, challenging Zhang and Qie's (2024) conclusion of continuous deterioration based on cropland utilization time series data from 2000 to 2020.

The identification of these distinct phases contributes methodologically to abandonment research, as various studies have identified different turning points in the temporal characteristics of cropland abandonment due to variations in data sources and research periods. For instance, Wang *et al.* (2023) analyzed spatiotemporal characteristics of abandoned cropland from 1991 to 2018, identifying a yearly increase from 1991 to 2008, stability from 2008 to 2011, and annual decreases from 2011 to 2018. This differs somewhat

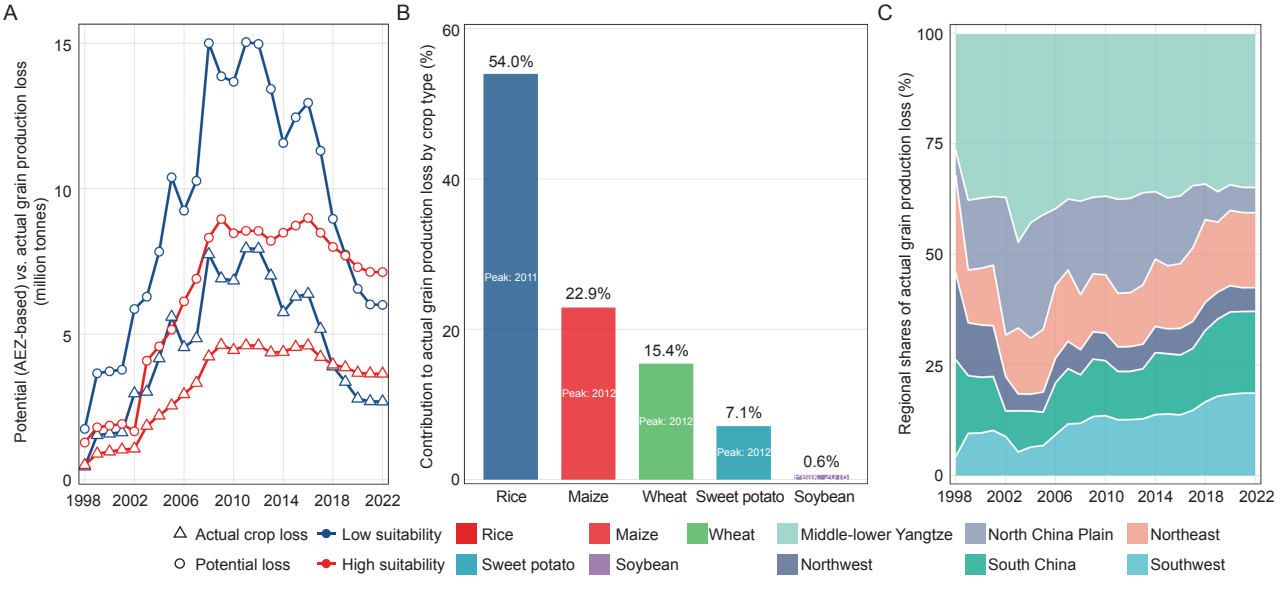


Fig. 6 Temporal and spatial patterns of grain production loss from abandoned cropland in China (1998–2022). A, potential (AEZ-based) *vs.* actual grain production loss (million tonnes) by land suitability class. B, contribution to actual grain production loss by crop type. Bars represent percentage contribution of each crop to total loss, with peak years indicated for each crop. C, regional shares of actual grain production loss over time. Stacked areas represent proportional contributions of six major agricultural regions.

from our findings of accelerated increases after 2003–2016. These discrepancies may be attributed to two factors: first, the statistical criteria for cropland abandonment changed during 2000–2003 with the initiation of the Grain for Green Program; second, our study employs a longer time series, enabling more detailed phase characterization.

Each identified phase corresponds to specific socioeconomic transitions in China's rural development, demonstrating the coupling relationship between abandonment trends and macroeconomic changes. From the late 1990s to the early 2000s, China effectively protected farmers' enthusiasm for grain production and contained cropland abandonment through measures such as increasing agricultural input and stabilizing grain prices (Yu and Jensen 2010; Huang and Yang 2017). This period coincided with the early stage of China's rural-urban transition, characterized by relatively balanced agricultural labor supply and demand. After 2003, factors including agricultural market reform, accelerated farmland transfer, and ecological land retirement led to declining comparative agricultural benefits and increased abandonment (Ma *et al.* 2022; Yin *et al.* 2024). This rapid increase phase (2003–2009) aligned with accelerated urbanization (increasing from 40.5% to 48.3%) and the extensive expansion of rural-urban migration, fundamentally altering rural labor structure.

The high-level fluctuation phase (2010–2016) represented a critical transition period where two opposing forces, agricultural support policies and rural demographic challenges, created complex abandonment dynamics. During this period, China implemented significant agricultural subsidies and support mechanisms, while simultaneously addressing severe rural aging and labor shortages. The subsequent decline phase (2017–2022) reflects the effectiveness of targeted rural revitalization strategies and enhanced land transfer mechanisms in stabilizing abandonment trends despite continued urbanization.

4.2. Spatial differentiation and typology of cropland abandonment

Our research reveals significant spatial heterogeneity in abandonment patterns across China's diverse geographical regions, extending beyond temporal dynamics. The study identifies southern China, particularly southwestern mountainous areas, as concentrated zones of cropland abandonment, primarily due to poor agricultural suitability. Analysis indicates that China's three northeastern provinces, Guangdong, and Fujian experience both occasional and long-term abandonment, mainly influenced by declining agricultural returns and population outflow (Liu *et al.* 2016; Xu *et al.* 2019). Southwestern mountainous regions predominantly experience long-term, progressive degradation abandonment, closely related to poor agricultural production conditions and environmental vulnerability (Han and Song 2020; Ma *et al.* 2022). These regional patterns demonstrate that abandonment manifests differently based on local biophysical conditions and socioeconomic contexts.

The spatial differentiation of abandonment is further elucidated through our typological framework, which identifies three distinct abandonment patterns across China's landscape. In regions with predominant single long-term abandonment (≥10 years), particularly in southwestern mountainous provinces, abandoned plots typically undergo complete ecological succession. These areas commonly transform into forest (10.8 years average duration) or grassland (7.5 years average duration), indicating active natural ecological succession processes. The duration analysis demonstrates that these areas have effectively transitioned from agricultural to natural ecosystems, representing permanent landscape changes rather than temporary abandonment.

Progressive degradation represents an intermediate abandonment pattern characterized by sequential land cover transitions. The conversion duration to forest and grassland in these regions (2.8 and 2.5 years, respectively) indicates gradual land use transformation. This pattern typically occurs in transitional landscapes between plains and mountains, where agricultural marginality increases due to both biophysical constraints and socioeconomic factors. The sequential nature of land cover changes in these areas, often from cropland to scrubland to forest or grassland, reveals a gradual ecological succession process distinct from other abandonment types.

Occasional abandonment (3–9 years) constitutes a distinct pattern primarily associated with more developed agricultural regions. In these regions, the conversion to forest land averages 4.3 years, while conversion to grassland takes 1.1 years. This pattern predominantly occurs in eastern coastal provinces with higher economic development levels, where abandonment is often triggered by short-term economic factors rather than biophysical constraints. The relatively brief duration of non-agricultural land cover transitions suggests a more dynamic and potentially reversible abandonment process compared to other types.

These three abandonment patterns demonstrate clear regional distribution characteristics that align with China's broader geographic and economic divisions. Eastern coastal regions predominantly experience occasional abandonment, reflecting their higher land values and economic alternatives. Central transitional zones display mixed patterns, while western and southwestern mountainous regions are characterized by long-term abandonment and progressive degradation, reflecting their challenging agricultural conditions and ongoing rural depopulation.

4.3. Interactive effects of agricultural suitability and labor migration on abandonment

The interaction between agricultural land suitability and labor migration shapes cropland abandonment patterns across regions in China. Analysis indicates that approximately 60% of abandonment occurred on marginal farmland with poor agricultural suitability, primarily in southwestern mountainous regions characterized by harsh natural conditions, high land fragmentation, and poor disaster resistance (Wang *et al.* 2020; Tian *et al.* 2023). In southwestern China (Chongqing, Guizhou and Yunnan), land areas with low cultivation suitability account for 54.38% of the total cropland. This concentration of abandonment on marginal lands follows economic rationality, with farmers prioritizing higher-quality

plots when facing labor constraints. However, the situation proves more complex than simple abandonment of marginal lands. Notably, 42.50% of abandonment occurred on high-quality cropland with better agricultural suitability. This abandonment of highly suitable cropland increased rapidly before 2010, reducing annual grain production capacity by over 10 million tonnes, demonstrating how socioeconomic factors can override biophysical suitability in abandonment decisions.

Labor migration is a key mediator in the relationship between land suitability and abandonment decisions. Analysis of the relationship between labor migration and cropland abandonment reveals multi-faceted dynamics that should inform differentiated regional land management policies. The non-linear relationship between long-term migration and abandonment, specifically the "moderate migration hypothesis", indicates that during early stages of rural-to-urban migration, increased non-agricultural income can support agricultural production through investments in mechanization, land transfers, or hired labor. However, beyond region-specific thresholds, excessive outflow of agricultural labor leads to severe labor shortages that cannot be offset by these mechanisms.

These regional patterns reflect China's heterogeneous agricultural systems and development levels. In eastern regions, which are economically developed with higher land values, the threshold for positive abandonment effects is relatively low (7.24%), indicating that even moderate labor outflows can trigger abandonment due to competitive alternative land uses. Conversely, the high threshold in central regions (37.08%) reflects a resilient agricultural system with effective land transfer mechanisms that can accommodate significant labor outflows before abandonment becomes problematic.

The spatial dimension of migration illuminates these complex dynamics. Our panel regression analysis quantified this relationship precisely: within-county migration significantly reduced abandonment rates (β=–0.005, P<0.01), while within-province migration significantly increased them (β=0.008, P<0.01). These contrasting effects demonstrate how the proximity between migration destinations and agricultural land critically influences farmers' ability to maintain cultivation while pursuing non-farm employment. Regional analysis revealed systematic differences in abandonment vulnerability: eastern provinces with higher agricultural development levels maintained stable abandonment rates below 5%, while southwestern provinces experienced progressive increases, reaching 5.91% in Yunnan by 2018–2022. These spatial patterns align with established mechanisms linking regional development and abandonment, including technological adoption capacity (Li *et al.* 2021), market integration levels (Tian *et al.* 2023), and infrastructure accessibility (Wang *et al.* 2020). Our findings extend Xie and Jiang's (2016) observation that circular migration patterns support continued agricultural production, while permanent distant relocation typically leads to land abandonment.

The interaction between migration and land suitability generates distinct regional abandonment outcomes. In regions with high agricultural suitability but significant labor outflows, land transfer markets serve as the critical mediating mechanism. Where these markets function effectively (as in central regions), abandonment remains limited despite substantial migration. Conversely, regions with both marginal land and high migration rates (as in southwestern mountainous areas) experience the most severe abandonment, creating a compounding effect that accelerates land use change.

4.4. Food security implications and differentiated policy recommendations

The intersection of cropland abandonment with China's food security objectives necessitates careful evaluation of production impacts and targeted policy responses. Our assessment reveals that grain production losses followed an inverted U-shaped pattern from 1998 to 2022, with peak potential losses of 15.0 and 8.8 million tonnes for low and high suitability land respectively in 2010, and actual losses peaking at 7.8 million tonnes for low suitability land (2010) and 4.6 million tonnes for high suitability land (2012). The diminishing difference between high and low suitability grain losses during 2018–2022 indicates a beneficial shift toward abandonment primarily affecting genuinely marginal rather than high-productivity cropland. Although the peak abandonment-induced grain loss represented a relatively modest proportion of national production (2.35% in 2010), these findings warrant consideration within China's broader food security framework. With China's grain self-sufficiency policy target exceeding 95%, even moderate production losses become significant when combined with other challenges including urbanization-driven farmland loss (approximately 1.5 million ha annually) and declining per capita arable land (reaching a critical threshold of 0.09 ha per person by 2020).

Crop-specific and regional analyses reveal differentiated food security implications across China's agricultural landscape. Rice dominated production losses, accounting for 54.0% of total actual grain loss, followed by maize (22.9%), wheat (15.4%), sweet potato (7.1%), and soybean (0.6%). This concentration in staple grains (collectively representing 92.3% of total impact) highlights significant food security concerns, particularly as peak losses for these crops coincided with China's high-level abandonment phase (2010–2016). The regional distribution of losses exhibited persistent spatial heterogeneity, with the Middle-Lower Yangtze region's contribution decreasing from 35% to 25% over the study period, while the North China Plain maintained a stable 20%–25% contribution. The northeastern region demonstrated the most pronounced temporal variation, while South China, Northwest, and Southwest regions collectively accounted for 30%–35% of total grain loss. These regional patterns reflect specific interactions between biophysical constraints, socioeconomic transitions, and policy environments. Moreover, regional implications were substantially more pronounced than the national data suggest, with abandonment causing grain production losses exceeding 8% of local production capacity in key southwestern provinces,

potentially threatening regional food security and rural livelihoods.

The differentiated regional and crop-specific impacts of abandonment require tailored policy responses. For the Middle-Lower Yangtze and North China Plain regions, where rice and wheat losses on high-suitability land predominate, policies should prioritize land consolidation, agricultural intensification, and mechanization. In the Northeast, characterized by fluctuating maize production losses, enhanced land transfer mechanisms and seasonal labor support systems provide more appropriate interventions. For western regions with predominantly low-suitability abandonment, a dual strategy combining ecological restoration on marginal lands with targeted high-efficiency agriculture on suitable plots represents the optimal approach. Recent policy developments have partially addressed these needs through strengthened protection of permanent basic farmland, accelerated high-standard farmland construction, and increased agricultural support measures (Huang and Yang 2017; Hao *et al.* 2024). These interventions have enhanced the comparative returns from quality cropland, consequently moderating abandonment impacts on grain production capacity through regionally differentiated approaches.

4.5. Research limitations and future directions

This study presents several methodological limitations that indicate specific directions for future research. First, while the study utilized ESA land cover data to construct land use evolution trajectories depicting China's cropland abandonment patterns at the macro scale, it lacks detailed characterization of local-scale processes, particularly at the household level. Future research should incorporate high-resolution remote sensing imagery combined with field survey data for more detailed abandonment process analysis. Second, the land use trajectory analysis approach, although effective for historical pattern identification, has limited predictive capability compared with other methodological frameworks. Alternative approaches such as cellular automata models, agent-based simulations, and machine learning methods provide stronger predictive functionality but often with less emphasis on empirical pattern detection. This methodological limitation becomes particularly relevant when considering future abandonment scenarios. Third, the assessment of food security implications relied on the 2000 China Cropland Production Potential dataset as a benchmark throughout the 1992–2022 period. While this dataset provides comprehensive coverage of China's major crops and cropping systems, it does not capture temporal changes in production capacity due to technological advancements, climate change impacts, or soil quality evolution.

Future research should address these limitations through methodological integration and expanded scope. Given that future climate change may alter agricultural planting conditions, increasing food demand will create new pressure on cropland resources, and rural population aging may intensify cropland abandonment, future research would benefit from combining empirical trajectory analysis with simulation techniques such as multi-agent modeling. These integrated approaches should incorporate factors including climate change, demographic structure, agricultural trade, and technological progress to simulate dynamic evolution processes under different policy scenarios, assess risk areas, and provide scientific basis for cropland protection and food security policies. Such methodological integration would maintain the empirical strengths of trajectory analysis while enhancing predictive capabilities, particularly for exploring how the regional migration thresholds identified in this study might interact with changing climate and demographic conditions.

5. Conclusion

This study examines China's cropland abandonment dynamics from 1998 to 2022 based on an analysis of land use trajectories from 1992 to 2022. Results reveal that cropland abandonment in China evolved through four distinct phases: slow growth (1998–2002, 0.91%), rapid increase (2003–2009, annual increase of 0.35 percentage points), high-level fluctuation (2010–2016, peak of 3.98%), and gradual decline (2017–2022, 3.01%). These phases correspond to specific socioeconomic transitions in China's rural development, demonstrating the coupling relationship between abandonment trends and macroeconomic changes. Spatiotemporal analysis identified three predominant abandonment patterns with distinct characteristics: single long-term abandonment (≥10 years), progressive degradation, and occasional abandonment (3–9 years). High abandonment rates (>15%) were concentrated in marginal agricultural areas, particularly southwestern mountainous regions and northeastern provinces, while traditional agricultural regions maintained rates below 5%. Duration analysis quantified significant regional differences in ecological succession: abandoned plots in southwestern regions showed longer conversion periods to forest (10.8 years), compared to eastern regions (4.3 years), indicating differentiated ecological transition processes across geographical contexts.

The relationship between abandonment, agricultural suitability, labor migration, and food security exhibited notable complexity. Quantitative assessment showed that while 57.50% of abandonment occurred on low-suitability land, 42.50% affected high-suitability cropland. Grain production loss analysis revealed an inverted U-shaped temporal pattern, with potential losses peaking at 15.0 and 8.8 million tonnes for low and high suitability land respectively in 2010, while actual losses peaked at 7.8 million tonnes for low suitability land (2010) and 4.6 million tonnes for high suitability land (2012). Crop-specific analysis determined that rice accounted for 54.0% of production losses, followed by maize (22.9%) and wheat (15.4%). Panel regression analysis identified significant non-linear relationships between labor migration and abandonment, with region-specific thresholds (eastern: 7.24%, western: 9.58%, northeastern: 13.93%, central: 37.08%) where migration effects changed direction. Short-distance migration significantly reduced abandonment rates, while medium-distance migration significantly increased them.

These findings suggest that effective management of cropland abandonment requires regionally differentiated

strategies based on land suitability, abandonment patterns, and labor dynamics. Agricultural intensification appears more appropriate for high-suitability areas with significant staple grain losses, while ecological restoration may be more suitable for long-term abandoned marginal lands. Labor migration policies should incorporate regional thresholds and spatial distance effects in their design. Further research integrating high-resolution remote sensing with simulation techniques could enhance predictive capabilities and policy formulation for cropland protection and sustainable rural development.

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Declaration of competing interest

The authors declare that they have no conflict of interest.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this manuscript, the authors used ChatGPT 4.0 to assist in improving the clarity and readability of the language. All content generated was carefully reviewed and revised by the authors as necessary, and the authors take full responsibility for the final content of the article.

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