

Article

Assessing Cultivated Land Abandonment in Hainan Island: Spatio-Temporal Differentiation and Driving Mechanism

Anqi He ¹, Liangxun Xu ^{2,*}, Xiaojuan Liu ³ and Tong Tian ¹

¹ Hainan Tang Huajun Academician Workstation, Key Laboratory of Applied Research on Tropical Crop Information Technology of Hainan Province, Institute of Scientific and Technical Information, Chinese Academy of Tropical Agricultural Sciences, Haikou 571101, China; heanqi@catas.cn (A.H.)

² Hainan Scientific Research Workstation for Tropical Island Territorial Governance and Ecological Restoration, Hainan Provincial Land Reserve, Consolidation, and Trading Center, Haikou 570203, China

³ Hainan Geomatics Center, Ministry of Natural Resources, Haikou 570203, China; liuxiaojuan@hainan.gov.cn

* Correspondence: bff117@163.com

Abstract

Cultivated land abandonment poses a growing threat to regional food security and sustainable land resource allocation in tropical island regions, making the accurate identification of its spatio-temporal characteristics and driving mechanisms an urgent research priority. This study addresses existing research gaps by examining cultivated land abandonment in Hainan Island from 2000 to 2025. Utilizing multi-temporal remote sensing images and a geographical detector model, this study analyzes the spatio-temporal evolution patterns and driving mechanisms of abandonment. The findings indicate that the scale of abandoned cultivated land exhibits a phased trend characterized by sharp expansion, significant contraction, and minor fluctuations. Spatially, it displays a pattern of higher values in the northeast and lower values in the southwest, with coastal areas exhibiting greater abandonment than inland regions. Natural factors serve as fundamental constraints, socio-economic factors act as the primary driving forces, and locational factors have gradually assumed dominance. All factors demonstrate a two-factor enhancement effect following interaction. This study underscores the necessity for region-specific strategies to mitigate cultivated land abandonment and promote sustainable agricultural development in tropical island areas.

Keywords: Hainan Island; cultivated land abandonment; spatio-temporal differentiation; geographical detector; driving mechanism; remote sensing



Academic Editor: Georgios Koubouris

Received: 9 June 2026

Revised: 21 July 2026

Accepted: 24 July 2026

Published: 3 August 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and

conditions of the [Creative Commons](#)

[Attribution \(CC BY\)](#) license.

1. Introduction

Human activities have significantly transformed land use and land cover globally [1]. The progressive conversion of natural surfaces into artificial or agricultural land, particularly land consumption, has become a major concern for contemporary societies, given its implications for environmental sustainability and the long-term availability of land resources [2,3]. Within this broader context, arable land remains a fundamental resource for ensuring national food security, promoting rural revitalization, and fostering sustainable economic and social development [4,5]. In China specifically, despite the implementation of a stringent farmland protection system that has stabilized the total area of farmland nationally, persistent issues related to farmland quality, spatial distribution, and utilization efficiency continue to undermine these protective gains [6,7].

Farmland abandonment is a major problem in parts of Europe, particularly in mountain areas and semiarid environments [8]. The process of urbanization and industrialization in developed countries is relatively early [9]. The advancement of industrialization and urbanization, coupled with the migration of rural labor to non-agricultural sectors, has led to a decline in the comparative benefits of agriculture. In certain regions, farmland has transitioned from seasonal abandonment to perennial abandonment, which hinders stable grain production and the establishment of high-standard farmland [10,11]. Consequently, conducting research on the spatio-temporal evolution and driving mechanisms of farmland abandonment is of great practical significance.

Studies have shown that land abandonment in China has exhibited a trend of spatial agglomeration and local diffusion over the past two decades, characterized by significant phased and regional differentiation [12]. Both domestic and international scholars have conducted extensive research on land abandonment. In terms of spatio-temporal pattern identification, various methods utilizing medium- and high-resolution multi-temporal remote sensing data have been employed to accurately depict the dynamics and distribution of abandonment across different regions [13].

Cultivated land abandonment constitutes a global phenomenon that poses a significant threat to both the ecological environment and food security [14]. Accordingly, both domestic and international scholars have conducted extensive research on farmland abandonment, particularly regarding its driving mechanisms. Existing studies have identified labor withdrawal and cultivated-land fragmentation as primary causes, with geographical detector models widely applied to assess the driving effects of multiple factors on land use transformation [15]. However, existing research lacks a systematic integration of spatio-temporal evolution, abandonment classification, driving-factor detection, and control strategies, and further refinement of control measures for specific units, such as tropical monsoon climate zones, remains necessary [16,17].

Since 1990, China's rapid industrialization and urbanization have converted approximately 2.94×10^5 hm² of cultivated land to non-agricultural use annually, directly threatening national food security [18]. Against this backdrop, Hainan Island becomes central. It can play a specific role in this context. As a unique tropical agricultural base and southern seed industry hub, it holds an irreplaceable strategic position in ensuring the supply of the country's winter "vegetable basket" and safeguarding the seed industry's security. The island's terrain is characterized by plains, plateaus, and hills, resulting in a complex agricultural planting structure.

Climate extremes increasingly threaten cultivated land use, as its utilization remains highly sensitive to seasonal climate variability and market fluctuations [19,20]. Hainan has been established as the largest special economic zone in China since 1988 [21]. With the establishment of the Hainan Free Trade Port and the restructuring of rural industries, the issue of abandoned farmland on Hainan Island has become increasingly prominent and spatially diverse [22]. This situation arises from constraints related to natural resources, fragmented farmland, and an aging labor force, thus posing a challenge to regional food security. In this context, clarifying the spatio-temporal evolution patterns of farmland abandonment, quantifying the spatio-temporal differences, and analyzing the driving factors are of great practical significance for formulating differentiated farmland control policies.

This study focuses on Hainan Island as the research area. Utilizing six periods of remote sensing images from 2000 to 2025, we apply a time sliding window discriminant model, a measurement of cultivated land abandonment rates, and a geographical detector model to illustrate the spatio-temporal characteristics of cultivated land abandonment. This analysis is conducted from three dimensions: the identification of abandoned land patterns, an analysis of spatio-temporal evolution, and the detection of driving factors. By

quantifying the intensity and interactions of natural, socio-economic, and locational factors, this study aims to reveal the formation mechanisms and differentiation characteristics of farmland abandonment in island-type regions. Ultimately, the findings are intended to provide scientific support and practical references for farmland reclamation, optimal allocation of farmland resources, farmland protection, and rural revitalization.

2. Theoretical Framework

2.1. Man–Land Relationship Areal System and Cultivated Land Use Transition Theory

The Man–Land Relationship Areal System and cultivated land-use transition theory provide the conceptual basis for this study, but they are used here in an operational rather than purely abstract manner [23,24]. Cultivated land abandonment is interpreted as a spatial outcome of weakened coordination among agricultural labor, land resources, production returns, ecological constraints, and policy intervention. In Hainan Island, urbanization, rural labor out-migration, terrain fragmentation, and tropical climatic disturbance jointly reshape the cost–benefit balance of cultivation. This framework therefore guides the selection of measurable variables for the empirical analysis.

2.2. Multi-Dimensional Driving Mechanisms and Spatio-Temporal Differentiation of Cultivated Land Abandonment

Land abandonment is a process widespread across many regions of the world, driven by socio-economic conditions and shifts in land use [25]. Building on this understanding, the present study organizes its empirical framework around three groups of measurable drivers: natural constraints (slope, farmland fragmentation, precipitation, and extreme weather), socio-economic pressure (farmer income, agricultural output, cultivated-land benefits, planting costs, and labor turnover), and locational conditions (population density, aging, urbanization, and distance to towns, roads, and settlements). Based on this framework, the Geographical Detector model is applied to test how these variables explain spatial heterogeneity in abandonment, and how their interactive effects evolve across the 2000–2010, 2010–2020, and 2020–2025 stages.

2.3. Cross-Scale “Monitoring-Analysis-Control” Comprehensive Analysis Framework

The framework follows a concise “monitoring-analysis-control” sequence (Figure 1). Multi-temporal remote sensing images are first used to identify the scale, grade, and spatial pattern of abandonment. Center-of-gravity analysis and Geodetector models then quantify spatial movement, dominant drivers, and interaction types. The results are finally translated into differentiated governance zones. Figure 1 has been reformatted as an operational workflow with unified English labels, font sizes, and caption style.

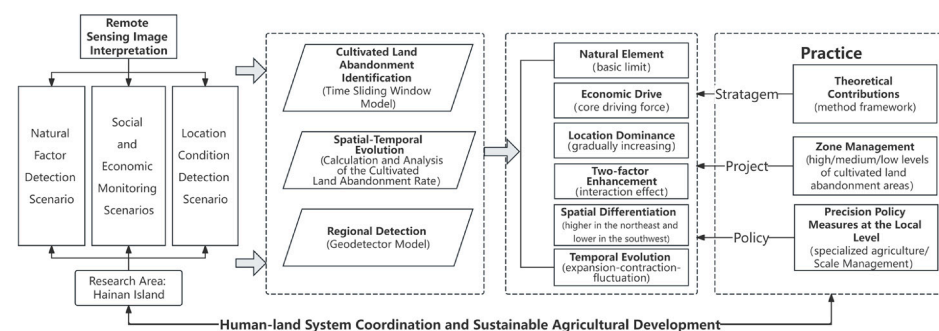


Figure 1. Operational framework for monitoring, mechanism analysis, and governance zoning of cultivated land abandonment in Hainan Island.

3. Materials and Methods

3.1. Overview of the Study Area

Hainan Island, situated at the southernmost tip of China, has geographical coordinates ranging from 18°10' to 20°10' N and 108°37' to 111°03' E. It experiences a tropical marine monsoon climate characterized by abundant sunlight and warmth, with an average annual temperature ranging from 22.5 to 25.6 °C and annual precipitation between 1600 and 2000 mm. The island's topography features a high central region, surrounded by lower areas, with a stepwise transition from Wuzhishan and Yingge Ling to the coastal zones, which include mountains, hills, plateaus, and plains (Figure 2).

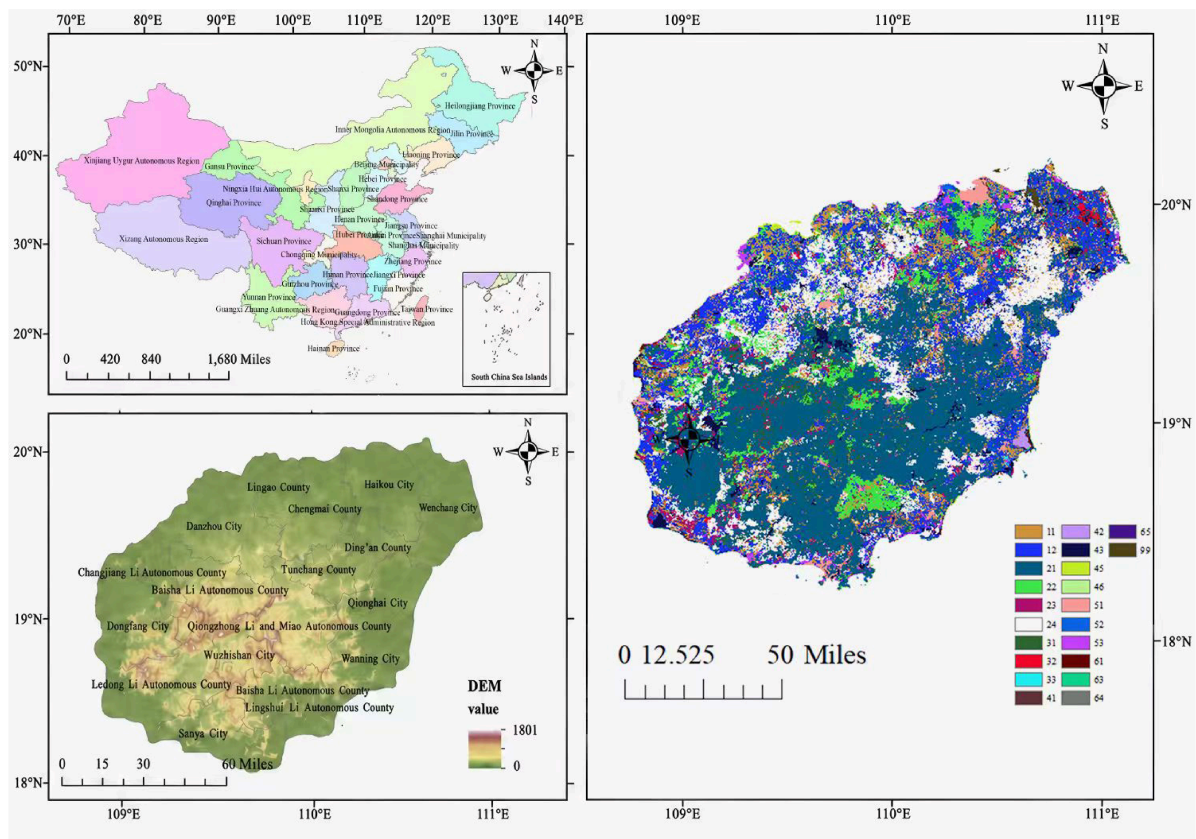


Figure 2. Geographical Location, Elevation, and Land Use Type Distribution Map of Hainan Island. Note: 11: Paddy field; 12: Irrigated arable land; 21: Orchard; 22: Tea plantation; 23: Other plantation; 24: Forest land; 31: Natural grassland; 32: Artificial grassland; 33: Other grassland; 41: Urban land; 42: Rural residential land; 43: Independent industrial; 45: Transportation land; 46: Mudflat; 51: Rivers and canals; 52: Lakes; 53: Reservoirs and ponds; 61: Tidal flat; 63: Estuarine delta wetland; 64: Coastal lagoon; 65: Shallow sea water; 99: Idle land.

High-quality farmland is predominantly located in the coastal plains and river terraces. In contrast, the central and hilly areas exhibit fragmented and sloping farmland, which poses a higher risk of being left uncultivated. The influence of monsoon patterns and topography results in uneven precipitation both temporally and spatially, with only 20% of the annual precipitation occurring during the dry winter and spring seasons. Seasonal water shortages, coupled with aging water conservancy infrastructure, have further exacerbated the instability of agricultural production.

As China's sole free trade port, characterized by its unique attributes and a significant breeding base in the south, Hainan faces unbalanced regional development. The eastern and northern coastal areas boast a developed economy, high levels of urbanization, and a notable aging and hollowing out of the agricultural labor force.

In contrast, the ecological conservation areas in the central and western regions lag economically, resulting in a lack of enthusiasm among farmers for grain cultivation. Recently, the structural adjustment of tropical efficient agriculture and the expansion of construction land have exerted dual pressure on farmland, leading to issues of ‘non-grain use’ and abandonment. This situation highlights the contradiction between population growth and land use, providing a typical case study for exploring the spatio-temporal evolution and driving mechanisms behind farmland abandonment.

3.2. Data Sources and Preprocessing

The data on abandoned farmland in Hainan Island was obtained through the interpretation of Landsat remote sensing images from six time points: 2000, 2005, 2010, 2015, 2020, and 2025. This data was sourced from the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (<http://www.resdc.cn>), with a spatial resolution of 30 m. The correction of this data was conducted in conjunction with the land use/cover product released by the National Earth System Science Data Center and the current land use map of Hainan Island.

DEM data was acquired from the Geospatial Data Cloud Platform. Among the natural factor data—average altitude, average slope, average annual temperature, and annual rainfall—altitude and slope were extracted from the DEM using ArcGIS 10.8.2. In contrast, temperature and rainfall data were sourced from the Statistical Yearbook. Socio-economic data, including urbanization rate, the proportion of secondary and tertiary industries in GDP, total agricultural machinery power, and road network density, were obtained from the Hainan Statistical Yearbook (2001–2025) and the statistical bulletins on national economic and social development for each county (city).

Location factor data, such as distances from farmland to rivers and settlements, were calculated in ArcGIS using tools like clipping and nearest neighbor analysis, based on the 2017 version of the National Basic Geographical Information Database. Data pre-processing involved unified projection transformation, void filling, and patch filtering of multi-period land use data to eliminate categorical noise. Through spatial overlay analysis and data standardization, a comprehensive dataset encompassing natural, social, and locational factors was constructed to support subsequent analyses of the spatio-temporal evolution and driving mechanisms of abandoned farmland.

Extreme weather (X4) was operationalized using two complementary indicators. First, we calculated the annual number of days with daily precipitation exceeding the 95th percentile threshold of the baseline climatology (2000–2025) for each county’s representative meteorological station. Second, we counted the annual frequency of tropical cyclone events that either made landfall on Hainan Island or passed within a 200 km radius of the island’s coastline. These two indicators were combined into a composite extreme weather index for each county-year. Data were obtained from the China Meteorological Administration Data Service Center (<https://data.cma.cn>) and the Hainan Statistical Yearbook. To account for inter-annual variability and align with the study’s temporal analysis periods (2000–2005, 2005–2010, 2010–2015, 2015–2020, 2020–2025), a five-year moving average of the composite index was calculated for each observation period. This temporal aggregation ensures that the extreme weather variable captures sustained climatic stress rather than single-year anomalies, making it compatible with the five-year interval structure of the remote sensing data.

3.3. Research Methods

3.3.1. Methods for Identifying Abandoned Farmland

Drawing on prior research on the extraction of abandoned farmland, this study constructs a time-sliding window discriminant model based on 30 m resolution land-use data to identify abandoned farmland at the pixel scale. In this study, abandonment is defined as a cultivated pixel that converts to natural cover, including forest land, grassland, or shrub land, while excluding conversion to construction land, and that does not revert to cultivation within the subsequent observation nodes [6,10,13]. This definition is ecologically meaningful, as forested and grassland areas play a significant role in supporting human livelihoods and regional ecosystem services [26].

The sampling years are 2000, 2005, 2010, 2015, 2020, and 2025. Because the dataset is organized at five-year intervals, the “six-year sliding window” used in this study refers to a six-node sampling sequence rather than six consecutive calendar years. The pixel classification includes continuous cultivated land, abandoned land, temporary fallow land, newly added cultivated land, and continuous non-cultivated land. Natural land does not include impermeable construction land, which avoids treating permanent construction conversion as agricultural abandonment. To mitigate classification noise, a 3×3 neighborhood majority filter was applied, and misclassified patches were corrected by integrating high-resolution image interpretation and field investigation in representative sample areas. The resulting maps were used to calculate abandoned farmland area and abandonment rates for each county.

3.3.2. Rate of Abandoned Farmland

The cultivated land abandonment rate refers to the proportion of abandoned cultivated land area relative to the total cultivated land area within the study region [27], calculated using the following formula:

$$P_i = (A_i/S_i) \times 100\%,$$

In the formula, P_i represents the cultivated land abandonment rate (%); A_i denotes the area of abandoned cultivated land; and S_i denotes the total area of cultivated land. Temporary fallow or restored cultivated land is not included in A_i .

3.3.3. Geographical Detector

The Geodetector model is a widely used method for examining spatial heterogeneity and for quantifying the explanatory power of potential driving factors [28]. Other spatial statistical approaches, such as the Getis-Ord statistics [29], could also be considered for spatial association analysis. This study applies both the factor detector and interaction detector modules to analyze the drivers of cultivated land abandonment in Hainan Island. The formula is as follows:

$$q = 1 - (1/(N \sigma^2)) * \sum_{h=1}^L (N_h \sigma_h^2),$$

In the formula, q represents the explanatory power of a driving factor for the spatial differentiation of the cultivated land abandonment rate, with a theoretical value range of [0, 1]. A q value closer to 1 indicates stronger spatial explanatory power. L denotes the number of strata; N_h and N represent the sample size in stratum h and the total sample size, respectively; σ^2 and σ_h^2 denote the variance of the abandonment rate for the whole study area and for stratum h , respectively.

To make the Geodetector implementation reproducible, the dependent variable Y is defined as the cultivated land abandonment rate (P_i) for each county-level analytical unit in each observation period. Explanatory variables are aggregated to the same spatial units

before factor detection: raster-based topographic, climatic, and fragmentation variables are summarized using cultivated-land pixels within each unit; distance variables are summarized by the mean distance of cultivated-land pixels to the nearest target feature; and socio-economic variables are matched from county-level statistical data.

For each factor, the analytical unit, number of units, discretization method, number of strata, within-stratum sample-size distribution, q value, and p value are reported together with the model results. Because q values approaching 1 can be inflated by small strata or over-discretization, q is interpreted as a measure of spatial explanatory association rather than direct causal magnitude. Continuous variables are examined under alternative stratification schemes, including equal interval, natural breaks (Jenks), and quantile classification; factors whose rankings remain stable across schemes are treated as robust drivers, whereas stratification-sensitive factors are discussed cautiously.

4. Results

4.1. Characteristics of the Spatio-Temporal Evolution of Abandoned Cultivated Land Area

Between 2000 and 2025, the scale of abandoned farmland on Hainan Island exhibited a phased change characterized by “sharp expansion, significant contraction, and moderate fluctuation.” In 2000, the area of abandoned farmland was approximately 89.84 km², representing a relatively low proportion of the total cultivated land and indicating sporadic abandonment. By 2005, the abandoned area had rapidly increased to 246.90 km², approximately 1.75 times the 2000 level. It continued to rise in 2010, reaching 248.71 km² and stabilizing at this high plateau. This trajectory of rapid expansion followed by a high-level plateau is consistent with patterns observed in other hilly and fragmented terrain regions [10,30].

Subsequently, driven by policies such as high-standard farmland construction and abandoned-land remediation, the abandoned farmland area decreased significantly to 64.34 km² in 2020 and then slightly increased to 68.52 km² in 2025. Overall, the problem has been alleviated during the recent policy period, although marginal agricultural areas still face persistent abandonment pressure.

From the perspective of temporal evolution, the period from 2000 to 2005 marked a phase of rapid expansion of abandoned farmland, with the area increasing by approximately 157 km². Correspondingly, the patches of abandoned farmland significantly increased in the northern regions of Danzhou, Lingao, and Chengmai, as well as in the eastern area of Wenchang, evolving from a scattered distribution to a more concentrated patch distribution.

From 2005 to 2010, the area of abandoned land remained at a high level, exhibiting small fluctuations. Spatially, it displayed a pattern characterized by “greater abundance in the north and lesser in the south, with more along the coast than inland.” The degree of contiguous abandoned land in the northern coastal plain and certain central hilly areas increased, reflecting a continuous trend of marginalization influenced by labor outflow and irrigation constraints.

From 2010 to 2020, influenced by policies aimed at rectifying abandoned land and eliminating “non-grain use” throughout the province, the area of abandoned land was significantly reduced. The scattered abandoned land in most areas saw a notable decrease, with only a few small-scale abandoned plots remaining in certain counties, such as Lingao and Wenchang. From 2020 to 2025, the area of abandoned land exhibited a moderate upward trend, primarily concentrated in the far northern suburbs and the eastern marginal agricultural areas. This trend reflects the reality that, following the diminishing marginal effects of policy interventions, some low-yield farmland continues to face the risk of abandonment.

In terms of the spatial distribution pattern, abandoned farmland exhibits characteristics of being relatively concentrated in the northern and eastern regions while being scattered in the central and southern areas. In the northern counties of Lingao, Chengmai, and Danzhou, as well as in the eastern coastal plain regions of Wenchang and Qionghai, the density of abandoned patches was significantly higher than the provincial average. At two time points, 2005 and 2010, relatively continuous high-value bands were formed. In 2025, these high-value areas remained concentrated in the far northern suburbs and eastern marginal agricultural areas (Figure 3).



Figure 3. Spatio-temporal evolution of abandoned farmland in Hainan Island.

These regions are predominantly traditional agricultural zones that were developed earlier, characterized by fragmented farmland and relatively weak irrigation facilities, making them highly susceptible to urban expansion, industrial transfer, and labor outflow. In contrast, mountainous and hilly regions such as Wuzhishan, Baoting, and Ledong in the central and southern parts of Hainan Island show a relatively small number of abandoned patches, mainly scattered and point-like. Overall, over the course of 25 years, abandoned farmland in Hainan Island has transitioned from low-level scattered abandonment to concentrated abandonment in the central mountainous areas such as Qiongzhang and Baisha, and then to overall contraction with residual abandonment in marginal agricultural areas.

4.2. Spatio-Temporal Evolution Characteristics of the Farmland Abandonment Rate

From 2000 to 2025, the levels of cultivated land abandonment on Hainan Island exhibited significant fluctuations. Based on the results of remote sensing image interpretation, cultivated land abandonment was classified into five severity levels, with Level 1 representing the least severe and Level 5 the most severe (Table 1). The spatiotemporal variations in abandonment levels were strongly correlated with regional natural conditions and spatial disparities in socio-economic development [31].

Table 1. Grades and types of abandoned farmland, along with their corresponding intervals.

Classification of Abandonment Level	Classification Interval of Cultivated Land Abandonment Rate (%)
Slight Abandonment (No Abandonment)	[0~10%]
Mild Abandonment	[10~30%]
Moderate Abandonment	[30~50%]
Severe Abandonment	[50~70%]
Extremely Severe Abandonment	[≥70%]

The five-class breakpoints (0~10%, 10~30%, 30~50%, 50~70%, and >70%) were determined using the Jenks natural breaks optimization method (which minimizes within-class variance and maximizes between-class variance) applied to the county-level abandonment rate distribution across all six periods, supplemented by expert judgment to ensure interpretability.

In 2000, cultivated land abandonment on Hainan Island exhibited significant spatial differentiation characteristics. The highest levels of abandonment (grade 5) were primarily concentrated in the central mountainous region, specifically Qiongzong and Baisha, and around Wuzhishan in the central region, displaying a block-like distribution. Areas with medium levels of abandonment (grades 2–3) were predominantly located around the perimeter of the island. In contrast, the lowest levels of abandonment (grade 1) were primarily found in Changjiang and Yazhou. The overall pattern reveals a gradient of severe abandonment in the central mountainous core and low abandonment in the coastal periphery. This aligns with the natural characteristics of high farmland fragmentation along the northeastern coast and the significant challenges associated with farming in the central mountainous region [32].

By 2005, a notable transformation occurred in the distribution pattern of abandoned land grades. The high-grade abandoned land areas (grade 5) expanded significantly, becoming confined to specific locales within central counties and cities such as Tunchang and Qiongzong. Additionally, areas classified as medium and above (grades 3–4) became more dispersed, with extensive tracts transitioning into medium abandoned land areas classified as grade 2–3. At the same time, the extent of low abandoned land areas (grades 1–2) expanded considerably. This change reflects the implementation effects of national agricultural support policies in tropical island regions [6].

In 2010, the spatial distribution of abandoned land grades was readjusted. The area of high-grade abandoned land (grade 5) retreated to the central core, shifting towards Qiongzong and Wuzhishan in the central region. Conversely, the area of medium-grade abandoned land (grades 3–4) expanded significantly, while the area of low-grade abandoned land decreased correspondingly [29].

This trend highlights the increasing pressure on cultivated land utilization due to the continuous loss of the labor force during that period. In 2015, the distribution of abandoned farmland grades continued to exhibit the central agglomeration feature observed in 2010. However, the area of high-level abandoned farmland (grades 4–5) diminished, primarily concentrated in the core mountainous regions of Qiongzong and Wuzhishan, as well as certain areas of Baisha, resulting in an ‘island-like’ mosaic distribution. Conversely, moderately abandoned areas (grades 3–4) extended into the surrounding hilly plateaus, encompassing Tunchang, Ding’an, and the western part of Qionghai, thereby forming a ring-shaped distribution band around the central mountainous area.

Low-grade abandoned areas (grades 1–2) expanded in clusters in Changjiang to the west and Yazhou and Ledong to the east and south, illustrating a gradient pattern characterized by ‘high in the middle and low around.’ This change reflects the ongoing impact of

labor force hollowing in the central ecological conservation area, as well as the inhibitory effects of large-scale agricultural operations on abandonment in the coastal plain areas surrounding the island. This observation is highly consistent with the developmental stage of tropical characteristic efficient agricultural structure adjustment [31,33]. The accelerated transfer of cultivated land during this period has also contributed to this pattern.

In 2020, the spatial pattern of farmland abandonment grades showed a general improvement. The incidence of high-grade farmland abandonment decreased and became more dispersed, while high-grade abandonment was confined to Qiongzong and Baisha, and the majority of counties returned to grade 1. Additionally, the area classified as low-grade abandonment experienced restoration and expansion, reflecting an overall trend towards dispersion and lower grades. This phenomenon is directly linked to the intensified efforts in farmland improvement on Hainan Island following the implementation of national poverty alleviation and rural revitalization strategies [7].

By 2025, new spatial characteristics in the distribution of farmland abandonment grades are anticipated. High-grade abandonment areas (grades 4–5) are projected to remain concentrated in the northern suburbs, marginal agricultural zones of Wenchang, and parts of Qiongzong. Medium-level abandonment (grades 2–4) is expected to persist in central regions such as Wuzhishan, Tunchang, and Qionghai, while western and southern areas will continue to exhibit relatively low abandonment levels (grades 1–3).

Overall, a distribution pattern characterized by “high grades in the northern suburbs and eastern fringes, medium grades in the central area, and low grades in the western and southern regions” is anticipated (Figure 4). This indicates that the differentiated characteristics of farmland abandonment across various regions are becoming more pronounced due to changes in population structure and locational conditions [34].

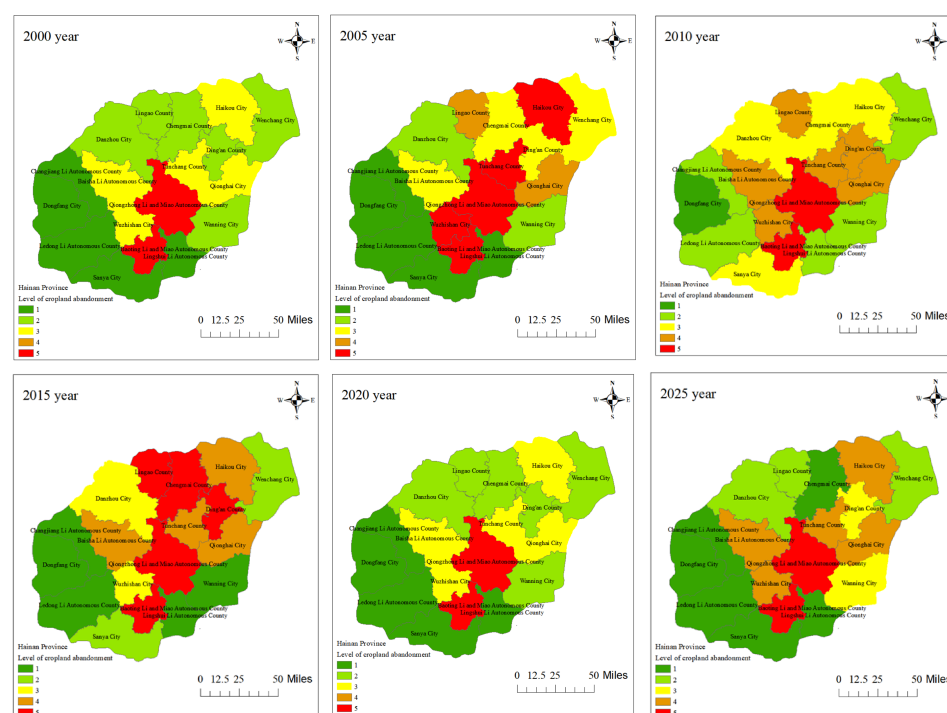


Figure 4. Spatio-temporal evolution of the cultivated land abandonment rate in Hainan Island.

Because single-dimensional classification limits inter-regional comparison to a superficial level, we further examine the underlying causes of graded spatial disparities by integrating regional natural endowments, population structure, and policy implementation. High-abandonment zones (Grade 4–5), concentrated in central mountainous towns such

as Qiongzong and Baisha, reflect the compounded effects of severe terrain constraints, farmland fragmentation, and continuous labor outflow.

Medium-abandonment zones (Grade 2–3) in the central hilly areas are shaped by seasonal drought and low agricultural profitability, producing temporary idling and localized risk rather than stable cultivation. Low-abandonment zones (Grade 1), located in the western and southern tropical planting areas, benefit from comprehensive irrigation infrastructure and high-value crop industrial chains that sustain farming enthusiasm and limit land idling. These spatial patterns are further shaped by the timing and intensity of policy intervention: the expansion of high-grade abandonment in 2005 coincided with rapid urbanization and unregulated labor migration, whereas the marked decline in abandonment grades by 2020 corresponds to the implementation of comprehensive abandoned-land remediation policies.

4.3. Shift in the Focus of Farmland Abandonment

As illustrated in Figure 5, the spatial center of gravity of abandoned farmland on Hainan Island exhibited phased and directional displacement from 2000 to 2025, with an overall shift toward the southwest. Specifically, the center of gravity moved 312.45 m southeast from 2000 to 2005, 89.63 m south from 2005 to 2010, 156.78 m southwest from 2010 to 2015, 47.21 m west from 2015 to 2020, and 203.34 m southwest from 2020 to 2025. The cumulative path length of these segment-by-segment movements was 809.41 m, whereas the net straight-line displacement between the 2000 and 2025 gravity-center coordinates was 749.41 m toward the southwest.

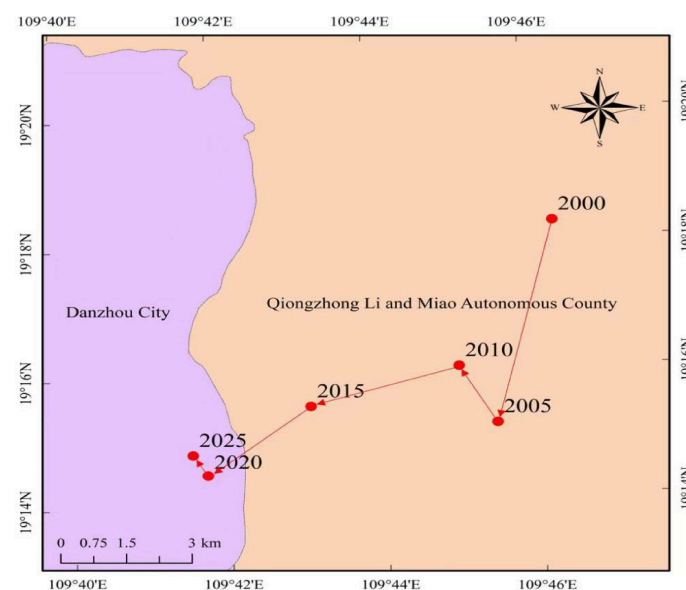


Figure 5. Shift of the center of gravity of cultivated land abandonment on Hainan Island. Note: The southwestward net displacement of the gravity center (749.41 m) reported in this paper refers to the straight-line Euclidean distance calculated between the gravity center coordinates from the years 2000 and 2025, rather than the simple algebraic sum of displacement distances for each sub-period. The migration distance for each stage denotes the path length of directional offset within the corresponding time interval, which cannot be directly summed to yield the total spatial offset. This distinction clarifies the difference between the cumulative migration path distance and the final net straight-line displacement of the gravity center.

These two values describe different distance concepts and therefore should not be directly equated. Significant disparities were also observed among abandonment levels: severely abandoned areas shifted 12,863.57 m southwest over 25 years, moderately abandoned areas shifted 5214.36 m southwest, and slightly abandoned areas shifted

421.89 m southward. The much larger grade-specific displacements are calculated from smaller and more discontinuous grade-specific patch subsets; they therefore describe re-distribution within each abandonment class and are not directly comparable with the all-abandonment centroid.

4.4. Analysis of the Driving Forces Behind Farmland Abandonment

To reveal the underlying mechanisms driving farmland abandonment, this study employs the geographical detector model and draws upon existing literature. It selects 15 indicators, encompassing natural factors, socio-economic factors, and locational factors, to analyze their impact intensity and interactions on farmland abandonment. The natural factors include slope (X1), farmland fragmentation (X2), precipitation (X3), and extreme weather (X4). Socio-economic factors comprise the per capita income of farmers (X5), agricultural output value (X6), economic benefits of cultivated land (X7), planting costs (X8), and labor turnover rate (X9). Locational factors consist of population density (X10), aging rate (X11), urbanization rate (X12), distance from towns (X13), distance from roads (X14), and distance from settlements (X15). All q values are interpreted as measures of spatial association rather than causal coefficients; q values close to 1 require particular caution and should be supported by p values, adequate within-stratum sample sizes, and stable rankings across discretization schemes (Figure 6).

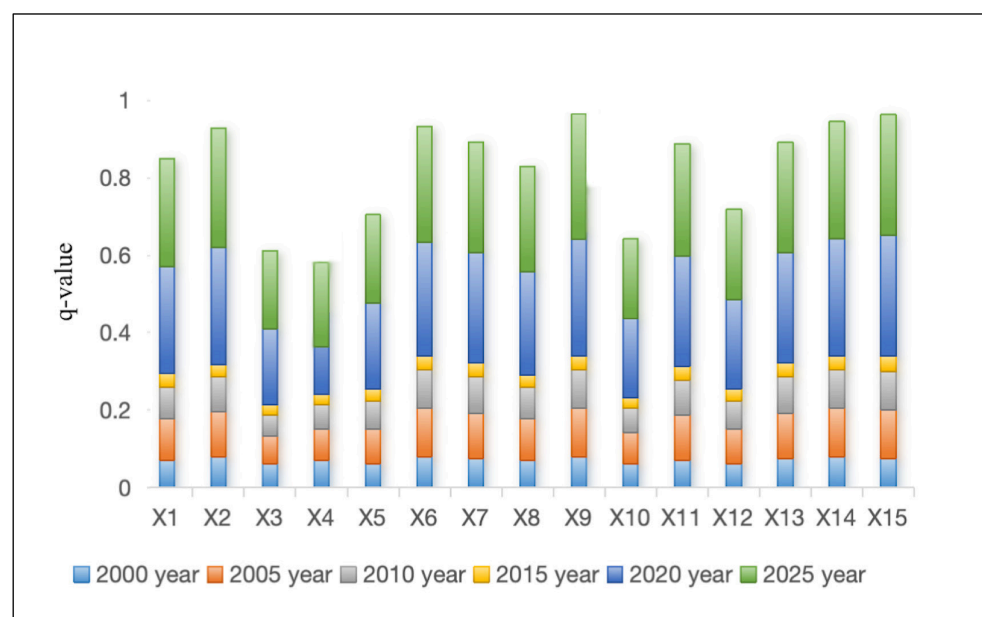


Figure 6. Geodetector q values for driving factors of cultivated land abandonment in Hainan Island (q range: 0–1).

4.4.1. Analysis of the Impact of Natural Factors

Natural factors represent the fundamental conditions influencing the abandonment of cultivated land [35]. In terms of temporal dynamics, the impact of natural factors on the abandonment of cultivated land exhibits significant fluctuations. It is highly correlated with policy interventions and improvements in agricultural production conditions. In 2000, the influence of natural factors was particularly pronounced. Among these, the p value for cultivated land fragmentation (X2) was the highest at 0.9240 ($q < 0.01$), indicating that the fragmentation of cultivated land plots is the primary natural factor restricting the utilization of cultivated land on Hainan Island. The influences of slope (X1) and precipitation (X3) were recorded at 0.8335 and 0.7827, respectively, both achieving significant levels, while the influence of extreme weather (X4) was comparatively weaker.

From 2005 to 2010, the influence of natural factors declined. By 2005, the p values for X2 and X1 had dropped to 0.6929 and 0.6968, respectively. In 2010, with the exception of X2 (0.5843), the influence of other natural factors weakened further, reflecting the positive effects of national agricultural support policies. The enhancement of agricultural production conditions alleviated the constraints imposed by natural conditions on the abandonment of cultivated land. In 2020, the influence of natural factors rebounded significantly, with p values for cultivated land fragmentation (X2) and precipitation (X3) at 0.8912 and 0.8012, respectively, while the slope (X1) recovered to 0.8710, and extreme weather (X4) was measured at 0.5892. By 2025, the influence of natural factors remained elevated, with p values for X2, X1, and X3 at 0.8765, 0.8542, and 0.7936, respectively, and X4 at 0.5918, indicating that the constraining effect of natural background conditions on marginal farmland abandonment continued to be significant even after the stabilization of policy effects.

Local effect: The high concentration of high-value natural factors and high-value abandoned land is primarily located in mountainous and hilly regions, such as Wuzhishan and Qiongzong in the central area. These regions are characterized by steep slopes and severely fragmented cultivated land, where the impact of natural conditions on abandoned land is significant. In contrast, the northern coastal plain exhibits low levels of both natural factors and land abandonment, indicating relatively weak constraints posed by natural conditions. By 2025, the area of high agglomeration is expected to slightly expand towards the marginal agricultural areas in the central region.

4.4.2. Analysis of the Impact of Socio-Economic Factors

Socio-economic factors are the primary driving force behind the abandonment of cultivated land [36]. The mechanisms are complex, dynamic, and closely intertwined with urbanization and industrial restructuring in Hainan Island. The agricultural output value (X6), defined as the total value of all agricultural products generated by agricultural production activities within a specific country or region over a designated period, remained a strong influence on abandonment. In 2000, the p -value of agricultural output value reached 0.8916, indicating that the profit disparity between marginal farmland and traditional agriculture was a core economic factor driving abandonment [37].

It remained high in 2020 (0.8918) and slightly decreased to 0.8763 in 2025. Concurrently, the economic benefits of cultivated land (X7) were 0.8810 in 2000, 0.8922 in 2020, and 0.8695 in 2025, suggesting that agricultural industrial transformation has had a sustained influence on abandonment.

The labor turnover rate (X9) also exhibited a sustained effect, with p values of 0.8907, 0.7596, and 0.5273 from 2000 to 2010, before rebounding to 0.8988 in 2020 and 0.8872 in 2025. This indicates that the out-migration of young and middle-aged rural labor is a long-term driver of farmland abandonment on Hainan Island [38]. Planting costs (X8) had a p -value of 0.8794 in 2000, declined from 2005 to 2015, rebounded to 0.6335 in 2020, and rose to 0.6847 in 2025. The per capita income of farmers (X5) exhibited a relatively weak influence, with p values not exceeding 0.65, suggesting that its impact on abandonment is less direct than that of labor loss and agricultural output value [39].

Concerning the local effect, the high-high concentration of socio-economic factors and abandonment is predominantly found in rapidly urbanizing areas such as Danzhou and Lingao in the north, as well as Wenchang in the east. These regions exhibit low comparative agricultural benefits and significant labor loss.

In contrast, tropical high-efficiency agricultural development areas, such as Dongfang in the west and Sanya in the south, demonstrate low-low agglomeration, characterized by high agricultural economic benefits and limited abandonment. In 2025, the high-high concentration area extended into the northern outskirts, where agricultural transformation

has been relatively slow. As arable land constitutes the foundation of farmers' livelihoods, this finding highlights the necessity of targeted land consolidation policies, rather than an assumption that urban-adjacent farmland carries inherently low abandonment risk [40].

4.4.3. Analysis of Location Factors

Location factors have a profound and lasting impact on the abandonment of cultivated land [41]. Against the backdrop of accelerated urbanization and population mobility, their influence exhibits characteristics of increasing over time and stabilizing. Among the distance factors, the distance from roads (X14) had a p -value of 0.9151 in 2000, recovered to 0.8967 in 2020, and was 0.9013 in 2025. The distance from towns (X13) and the distance from settlements (X15) had a significant influence in 2000 and 2005, rebounding to 0.83 and 0.90 in 2020, and reaching 0.8426 and 0.9138, respectively, in 2025. This indicates that the constraining effect of arable land accessibility on abandonment continues to strengthen [30,34]. Among the population structure factors, the aging rate (X11) had a p -value of 0.9048 in 2020.

It rose further to 0.9217 in 2025, consistently surpassing all other single factors to emerge as the strongest key factor for farmland abandonment. This reflects that the accelerated aging of the rural population in Hainan has rendered the lack of a young labor force the fundamental problem of land abandonment. The urbanization rate (X12) had a p -value of 0.6501 in 2000, rebounded to 0.5064 in 2020, and reached 0.5238 in 2025. Additionally, population density (X10) has a relatively weak impact, indicating that the relationship between abandoned farmland and population density is not simply linear [31].

Local effect: Location factors and the high concentration of abandonment are primarily distributed in the northern coastal far suburbs, which are distant from towns and roads and exhibit a high degree of population aging. In contrast, the areas surrounding towns demonstrate low agglomeration, characterized by good accessibility to arable land and a relatively balanced population structure. In 2025, areas of high concentration became more concentrated in the northern far suburbs and the eastern marginal agricultural regions.

4.4.4. Multi-Factor Interaction Analysis

The interaction detection results from the Geodetector were interpreted using the standard comparison among $q(X_i)$, $q(X_j)$, and $q(X_i_and_X_j)$. When $q(X_i_and_X_j)$ exceeds the larger single-factor q value but remains below $q(X_i)+q(X_j)$, the relationship is classified as dual-factor enhancement; when $q(X_i_and_X_j)$ exceeds $q(X_i)+q(X_j)$, it is classified as nonlinear enhancement. If an interaction q value remains high but does not exceed the strongest corresponding single-factor q value, it is reported as a high-intensity joint association rather than as an enhancement effect. This distinction prevents high interaction values from being overinterpreted.

In 2000, the overall interaction intensity was relatively strong. The interaction q value of X6-X14 (agricultural output value $\times$ distance from road) was the highest at 0.85, followed by X7-X8 (economic benefit $\times$ planting cost, 0.8465) and X6-X8 (agricultural output value $\times$ planting cost, 0.8331). The combined effect of agricultural economic conditions and geographical accessibility served as the core driver [8] of abandonment during that period. The interaction intensity remained high in 2005, with high q values for X5-X6 (income $\times$ output value, 0.8581) and X12-X6 (urbanization $\times$ output value, 0.8918), indicating prominent [28] cross-influence among socio-economic factors. In 2010, the strongest interaction was X2-X3 (fragmentation $\times$ precipitation, 0.8536), reflecting the mutual reinforcement of natural constraints [42].

The interaction q value of X14 with most factors ranged from 0.72 to 0.75, indicating a significant coupling effect of accessibility factors with other elements [15]. In 2020, interaction intensity rebounded, generally exceeding 0.6, with high joint q values such

as X11-X8 (aging $\times$ planting cost, 0.8218), X14-X10 (distance from road $\times$ population density, 0.7844), and X6-X14 (output $\times$ distance, 0.7629). By 2025, the joint effects remained high, with X11-X8 (aging $\times$ planting cost, 0.8672), X15-X11 (distance from residential area $\times$ aging, 0.8439), and X2-X11 (fragmentation $\times$ aging, 0.8265) among the leading interaction q values. These results indicate that population aging, economic costs, natural constraints, and spatial distance jointly shape later-stage abandonment, consistent with findings reported in previous studies [43,44]. However, the specific interaction category of each factor pair should be determined according to the formal q -value comparison rule, rather than inferred from the combined effect alone.

Interaction effects were classified based on the relationship between the interaction q -value and the individual explanatory power of each factor. Dual-factor enhancement occurs when $\max[q(X_i), q(X_j)] < q(X_i \cap X_j) < q(X_i) + q(X_j)$, while nonlinear enhancement occurs when $q(X_i \cap X_j) > q(X_i) + q(X_j)$. When interaction effects remain strong but do not exceed the explanatory power of the dominant single factor, they are considered high-intensity joint associations rather than enhancement effects.

During 2000–2010, interactions were mainly characterized by dual-factor enhancement, especially among natural and socio-economic factors. The combined effects of farmland fragmentation and precipitation variability increased abandonment risks by jointly constraining agricultural production conditions. During 2010–2020, policy interventions weakened the coupling effects between natural and socio-economic drivers, leading to an overall decline in interaction intensity. From 2020 to 2025, demographic and economic-location interactions became increasingly important, with population aging, planting costs, and accessibility barriers jointly shaping residual farmland abandonment patterns.

High-intensity interaction factors showed distinct spatial patterns. In the northern and eastern coastal plains (e.g., Lingao and Wenchang), farmland abandonment was mainly driven by the combined effects of labor outmigration and poor accessibility, where low agricultural returns and transportation constraints accelerated abandonment. In the central mountainous regions (e.g., Qiongzong and Wuzhishan), fragmentation and precipitation interactions dominated, as fragmented farmland and water constraints created persistent abandonment risks. In northern suburban marginal farmland areas during 2020–2025, aging farmers, high production costs, and spatial isolation formed a major compound pressure contributing to continued abandonment (Figure 7).

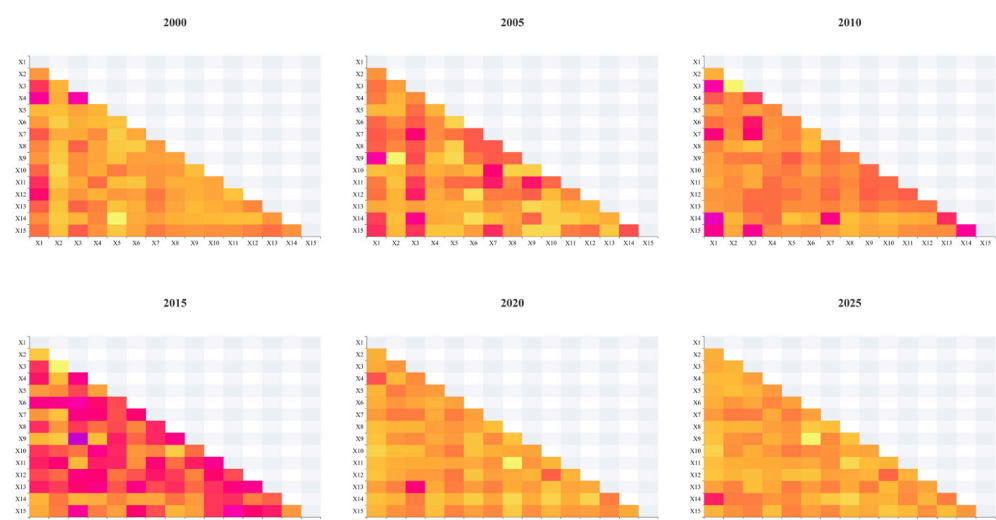


Figure 7. Interaction Factor Influence of Cultivated Land Abandonment on Hainan Island.

5. Discussion

5.1. Comparison with Existing Research Results

Cultivated land is the foundation of food production and an irreplaceable resource for human survival and the national economy [45]. This study reveals a distinct spatio-temporal pattern of cultivated land abandonment on Hainan Island, characterized by a gradient of “high in the central mountainous regions and low in the coastal areas, with inland hilly zones exhibiting higher abandonment rates than coastal plains exhibiting higher abandonment rates than inland areas.” Additionally, the temporal evolution of land abandonment is marked by phases of “rapid expansion, significant contraction, and minor fluctuations.” These findings align closely with existing research on land abandonment in tropical and subtropical regions of China, particularly studies that emphasize the dual influences of natural conditions and socio-economic transformations.

The higher abandonment rates observed in the central mountainous core (e.g., Qiongzong, Baisha) align with the findings of Chasia, S. et al. [38], who emphasized the influence of urbanization and labor migration on land marginalization. In contrast, the central and southern mountainous areas (e.g., Wuzhishan, Baoting) demonstrate lower abandonment rates, attributable to the smaller scale of cultivated land and the robust labor-absorbing capacity of traditional tropical cropping systems, as similarly noted by Wang, J.F et al. [15]. Furthermore, the southern and western regions benefit from abundant light and heat resources, well-developed irrigation infrastructure, and the large-scale cultivation of high-value cash crops, all of which enhance agricultural returns and mitigate abandonment—reflecting the general pattern observed in the southern hilly areas of China [39].

Temporally, the significant increase in abandoned farmland between 2000 and 2010 (from 89.84 km² to 248.71 km²) reflects the rapid processes of industrialization and urbanization that triggered a massive out-migration of the rural labor force [46]. The subsequent decline and stabilization of abandoned farmland (64.34 km² in 2020 and 68.52 km² in 2025) coincide with the implementation of national policies, including high-standard farmland construction, abandonment remediation programs, and agricultural subsidies. However, the fact that abandonment has not decreased further suggests the emergence of a “policy bottleneck,” a phenomenon also observed in other hilly and mountainous regions of southern China.

Notably, this study identifies population aging (X11) as the most significant single driver of land abandonment by 2025, surpassing economic factors such as agricultural output value and labor turnover rates. This finding offers a novel perspective on the evolving drivers of land abandonment in tropical island regions. It underscores the limitations of interventions that rely solely on economic or infrastructure-based solutions without demographic support.

5.2. Theoretical and Policy Implications

Promoting green utilization of cultivated land is the key to balancing resource use and ecological capacity [47]. The findings underscore the necessity for a multi-dimensional, phase-sensitive policy framework. First, differentiated regional strategies are required. In areas with high abandonment rates, particularly the central mountainous areas such as Qiongzong and Baisha, policies should prioritize land transfer, scale operations, and the development of modern agricultural parks. Conversely, the central and southern hilly regions should capitalize on their comparative advantages in tropical agriculture and under-forest economies to optimize land utilization. In addition to this, economic incentives can be a strong tool in this context. In other words, a dynamic, regionally differentiated subsidy

system should be established to support marginal farmland with low output value, thereby stabilizing farmers' incomes and reducing labor turnover.

Furthermore, there is a need for infrastructure improvement. Remote farmlands that are distant from roads and settlements should be prioritized for investment in transport and irrigation infrastructure to enhance accessibility and lower production costs. Lastly, the demographic support mechanisms can be helpful. In light of the increasing impact of aging populations, rural talent revitalization programs, including entrepreneurship subsidies, agricultural training, and community-supported agriculture models, are essential for sustaining a stable agricultural labor force.

5.3. Limitations and Future Research Directions

This study has several limitations. First, the 30 m spatial resolution of Landsat images may not adequately capture small-scale, fragmented abandonment patterns, particularly in complex terrains. Second, while the time-sliding-window discriminant model is effective for identifying perennial abandonment, it may underestimate seasonal or short-term temporary fallow cycles. Third, the Geodetector results are sensitive to spatial unit choice and continuous-variable discretization. Hainan has a limited number of county-level units, and very fine stratification may inflate q values when within-stratum sample sizes are small. Therefore, high q values are interpreted cautiously and should be accompanied by p values, stratum numbers, and within-stratum sample-size distributions. Fourth, although the index system includes extreme weather as X_4 , institutional variables such as land tenure security, detailed land-transfer arrangements, market price volatility, and event-level climate hazards are not fully represented because consistent long-term county-level data are difficult to obtain.

Future research should integrate higher-resolution remote sensing data, such as Sentinel-2, Gaofen imagery, and UAV validation samples, to improve the detection of fragmented abandoned plots. It should also apply OPGD or comparable optimized discretization, permutation-based significance testing, and sensitivity checks using equal interval, natural breaks, and quantile schemes. Household surveys, land-tenure records, land-transfer data, crop-price series, and typhoon/drought-event datasets would further strengthen the behavioral and institutional explanation of abandonment.

Furthermore, the five-grade classification used in this study relies solely on the abandonment rate and does not capture patch area or spatial connectivity. We therefore propose a composite index ($I = 0.60P_i + 0.25S + 0.15C$), incorporating abandonment rate (P_i), standardized average patch size (S), and connectivity (C), for refined risk zoning in future work. This index is designed to distinguish scattered small-scale abandonment (high P_i but low S and C) from contiguous high-risk zones (high P_i with high S and C). Future monitoring should adopt this index once consistent patch-level data becomes available for all periods. Future monitoring should adopt this index to distinguish scattered small-scale abandonment from contiguous high-risk zones once consistent patch-level data become available for all periods.

6. Conclusions

Based on multi-temporal remote sensing images spanning 2000–2025, this study systematically reveals the spatio-temporal evolution and driving mechanisms of cultivated land abandonment on Hainan Island, yielding four core conclusions.

First, abandonment followed a distinct three-phase trajectory: sharp expansion from 2000 to 2010 (peaking at 248.71 km²), significant contraction through 2020 (falling to 64.34 km²), and minor fluctuation thereafter (rising slightly to 68.52 km² by 2025). This pattern indicates that while overall governance has been broadly effective in curbing large-

scale abandonment, marginal farmland, particularly in fragmented or poorly accessible plots, remains persistently vulnerable and requires sustained monitoring rather than one-time intervention.

Second, abandonment displays clear and persistent spatial differentiation, with higher rates in the northeast and coastal zones than in the southwest and interior. High-value clusters have remained concentrated in the central highlands throughout the study period, while the core abandonment belt has gradually migrated from the northeastern coast toward marginal agricultural zones, a shift that signals evolving, rather than static, land-use pressure across the island.

Third, abandonment is driven by the evolving interplay of natural, socio-economic, and locational factors. Farmland fragmentation and slope act as fundamental physical constraints; agricultural output value and labor turnover serve as core socio-economic drivers; and, critically, locational factors such as population aging and distance from roads have become increasingly dominant in recent years. This progression reflects three distinct mechanistic phases—a “natural–economic dominant” stage (2000–2010), a “policy-intervention dominant” stage (2010–2020), and a “population–location dominant” stage (2020–2025)—with each transition validated by remote sensing inflection points, Geodetector q-value mutations, and corresponding agricultural land policy rollouts.

Fourth, building on this spatial and mechanistic differentiation, the study delineates three governance zones—primary priority zones, secondary regular-control zones, and tertiary low-risk conservation zones—each paired with tailored management strategies. Together, these findings offer an evidence-based, phase-sensitive framework for guiding cultivated land reclamation and sustainable agricultural governance across Hainan and comparable tropical island regions.

Author Contributions: Methodology, L.X. and A.H.; Data collection, processing and analysis, A.H. and T.T.; Writing—original draft, A.H., T.T. and X.L.; Writing—review and editing, L.X., X.L. and A.H. All authors have read and agreed to the published version of the manuscript.

Funding: Open Research Project of the Key Laboratory of Applied Research on Tropical Crop Information Technology of Hainan Province (ZDSYS-KFJJ-202505), Hainan Province’s Key Research and Development Project (ZDYF2026SXLH031).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are openly available in [Zenodo] at [10.5281/zenodo.20603159].

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Paudel, B.; Gao, J.; Zhang, Y.; Wu, X.; Li, S.; Yan, J. Changes in Cropland Status and Their Driving Factors in the Koshi River Basin of the Central Himalayas, Nepal. *Sustainability* **2016**, *8*, 933. [\[CrossRef\]](#)
2. Punzo, G.; Castellano, R.; Bruno, E. Using geographically weighted regressions to explore spatial heterogeneity of land use influencing factors in Campania (Southern Italy). *Land Use Policy* **2022**, *112*, 105853. [\[CrossRef\]](#)
3. Mirzoieva, T.; Heraimovych, V.; Loshakova, Y.; Tripak, M.; Humeniuk, I. Optimization of the sown areas structure as a tool for the development of medicinal crop production on the basis of sustainability and regenerative agriculture. *E3S Web Conf.* **2021**, *244*, 03027. [\[CrossRef\]](#)
4. Faye, B.; Du, G.; Li, Y.; Li, Q.; Diène, J.C.; Mbaye, E.; kama, R. Connecting the farmers’ knowledge and behaviors: Detection of influencing factors to sustainable cultivated land protection in Thiès Region, Senegal. *J. Rural Stud.* **2025**, *116*, 103634. [\[CrossRef\]](#)
5. Liu, X. Empowering rural revitalization in China with GAI: The application value, challenges, and optimization paths. *Cogent Food Agric.* **2025**, *11*, 2502389. [\[CrossRef\]](#)

6. Alcantara, C.; Kuemmerle, T.; Prishchepov, A.V.; Radeloff, V.C. Mapping abandoned agriculture with multi-temporal MODIS satellite data. *Remote Sens. Environ.* **2012**, *124*, 334–347. [\[CrossRef\]](#)
7. Perpiña, C.C.; Kavalov, B.; Diogo, V.; Jacobs, C.; Batista, E.S.F.; Lavalle, C. Agricultural Land Abandonment in the EU Within 2015–2030. 2018. Available online: <https://publications.jrc.ec.europa.eu/repository/handle/JRC113718> (accessed on 16 July 2026).
8. García-Ruiz, J.M.; Lana-Renault, N. Hydrological and erosive consequences of farmland abandonment in Europe, with special reference to the Mediterranean region—A review. *Agric. Ecosyst. Environ.* **2011**, *140*, 317–338. [\[CrossRef\]](#)
9. Lu, X.; Qu, Y.; Sun, P.; Yu, W.; Peng, W. Green Transition of Cultivated Land Use in the Yellow River Basin: A Perspective of Green Utilization Efficiency Evaluation. *Land* **2020**, *9*, 475. [\[CrossRef\]](#)
10. Estel, S.; Kuemmerle, T.; Alcántara, C.; Levers, C.; Prishchepov, A.; Hostert, P. Mapping farmland abandonment and recultivation across Europe using MODIS NDVI time series. *Remote Sens. Environ.* **2015**, *163*, 312–325. [\[CrossRef\]](#)
11. Prishchepov, A.V.; Ponkina, E.V.; Sun, Z.; Bavorova, M.; Yekimovskaja, O.A. Revealing the intentions of farmers to recultivate abandoned farmland: A case study of the Buryat Republic in Russia. *Land Use Policy* **2021**, *107*, 105513. [\[CrossRef\]](#)
12. Yang, Y.; Hobbie, S.E.; Hernandez, R.R.; Fargione, J.; Grodsky, S.M.; Tilman, D.; Zhu, Y.G.; Luo, Y.; Smith, T.M.; Jungers, J.M.; et al. Restoring Abandoned Farmland to Mitigate Climate Change on a Full Earth. *One Earth* **2020**, *3*, 176–186. [\[CrossRef\]](#)
13. Baumann, M.; Kuemmerle, T.; Elbakidze, M.; Ozdogan, M.; Radeloff, V.C.; Keuler, N.S.; Prishchepov, A.V.; Kruhlov, I.; Hostert, P. Patterns and drivers of post-socialist farmland abandonment in Western Ukraine. *Land Use Policy* **2011**, *28*, 552–562. [\[CrossRef\]](#)
14. Sun, Y.; Miao, Y.; Xie, Z.; Jiang, X. Address the challenge of cultivated land abandonment by cultivated land adoption: An evolutionary game perspective. *Land Use Policy* **2025**, *149*, 107412. [\[CrossRef\]](#)
15. Wang, J.F.; Li, X.H.; Christakos, G.; Liao, Y.L.; Zhang, T.; Gu, X.; Zheng, X.Y. Geographical Detectors-Based Health Risk Assessment and its Application in the Neural Tube Defects Study of the Heshun Region, China. *Int. J. Geogr. Inf. Sci.* **2010**, *24*, 107–127. [\[CrossRef\]](#)
16. Sroka, W.; Pölling, B.; Wojewodzic, T.; Strus, M.; Stolarczyk, P.; Podlinska, O. Determinants of Farmland Abandonment in Selected Metropolitan Areas of Poland: A Spatial Analysis on the Basis of Regression Trees and Interviews with Experts. *Sustainability* **2019**, *11*, 3071. [\[CrossRef\]](#)
17. Xiao, R.; Ling, J.; Fei, J.; Huang, J.; Wang, J. A Study on Spatiotemporal Differentiation Characteristics of Ecological Security and Sustainable Utilization of Cultivated Land in Sichuan Province Based on Emergy–Ecological Footprint Model. *Land* **2025**, *14*, 2025. [\[CrossRef\]](#)
18. Sun, Y.; Chang, Y.; Liu, J.; Ge, X.; Liu, G.J.; Chen, F. Spatial Differentiation of Non-Grain Production on Cultivated Land and Its Driving Factors in Coastal China. *Sustainability* **2021**, *13*, 13064. [\[CrossRef\]](#)
19. Gao, J.; Faye, B.; Tian, R.; Du, G.; Zhang, R.; Biot, F. Understanding the Impact of Climatic Events on Optimizing Agricultural Production in Northeast China. *Atmosphere* **2025**, *16*, 704. [\[CrossRef\]](#)
20. Faye, B.; Du, G.; Zhang, R.; Li, Y.; Ankrah Twumasi, M.; Xue, R.; Ankrah, M. Divergent provincial pathways for climate resilience and rural livelihood security in Northeast China: Insights from MM-QR analysis. *Cogent Food Agric.* **2026**, *12*, 2694820. [\[CrossRef\]](#)
21. Xiu, C.; Li, T. Construction of the Hainan Free Trade Port from the perspective of regional cultural development. *Front. Earth Sci.* **2023**, *10*, 1032953. [\[CrossRef\]](#)
22. Heyong, W.; Peng, W.; Zhengtong, H. Background of Hainan’s Customs Closure: Institutional Impact, Resource Restructuring, and Job-Housing Balance. *Sustain. Dev. Res.* **2026**, *8*, p49. [\[CrossRef\]](#)
23. Zhou, G.; Long, H. Explanation of land-use system evolution: Modes, trends, and mechanisms. *Land Use Policy* **2025**, *150*, 107470. [\[CrossRef\]](#)
24. Niu, S.; Lyu, X.; Gu, G.; Zhou, X.; Peng, W. Sustainable Intensification of Cultivated Land Use and Its Influencing Factors at the Farming Household Scale: A Case Study of Shandong Province, China. *Chin. Geogr. Sci.* **2021**, *31*, 109–125. [\[CrossRef\]](#)
25. Quintas-Soriano, C.; Buerkert, A.; Plieninger, T. Effects of land abandonment on nature contributions to people and good quality of life components in the Mediterranean region: A review. *Land Use Policy* **2022**, *116*, 106053. [\[CrossRef\]](#)
26. Faye, B.; Du, G.; Li, Q.; Véronique, H.; Faye, M.T.; Colee Diéne, J.; Mbaye, E.; Seck, H.M. Lessons Learnt from the Influencing Factors of Forested Areas’ Vulnerability under Climatic Change and Human Pressure in Arid Areas: A Case Study of the Thiès Region, Senegal. *Appl. Sci.* **2024**, *14*, 2427. [\[CrossRef\]](#)
27. Liu, X.; Zhang, Z.; Li, M.; Fu, Y.; Hui, Y. Spatial conflict simulation of land-use based on human-land-landscape elements intercoordination: A case study in Tianjin, China. *Environ. Monit. Assess.* **2022**, *194*, 317. [\[CrossRef\]](#) [\[PubMed\]](#)
28. Paudel, G.S.; Thapa, G.B. Changing farmers’ land management practices in the hills of Nepal. *Environ. Manag.* **2001**, *28*, 789–803. [\[CrossRef\]](#) [\[PubMed\]](#)
29. Getis, A.; Ord, J.K. The Analysis of Spatial Association by Use of Distance Statistics. *Geogr. Anal.* **1992**, *24*, 189–206. [\[CrossRef\]](#)
30. Khanal, N.R.; Watanabe, T. Abandonment of agricultural land and its consequences: A case study in the Sikles Area, Gandaki Basin, Nepal Himalaya. *Mt. Res. Dev.* **2006**, *26*, 32–40. [\[CrossRef\]](#)

31. Awasthi, K.D.; Sitaula, B.K.; Singh, B.R.; Bajacharaya, R.M. Land-use change in two Nepalese watersheds: GIS and geomorphometric analysis. *Land Degrad. Dev.* **2002**, *13*, 495–513. [\[CrossRef\]](#)
32. Deininger, K.; Savastano, S.; Carletto, C. Land Fragmentation, Cropland Abandonment, and Land Market Operation in Albania. *World Dev.* **2012**, *40*, 2108–2122. [\[CrossRef\]](#)
33. Anache, J.A.A.; Flanagan, D.C.; Srivastava, A.; Wendland, E.C. Land use and climate change impacts on runoff and soil erosion at the hillslope scale in the Brazilian Cerrado. *Sci. Total Environ.* **2018**, *622–623*, 140–151. [\[CrossRef\]](#) [\[PubMed\]](#)
34. Jamshidi, R.; Dragovich, D.; Webb, A.A. Distributed empirical algorithms to estimate catchment scale sediment connectivity and yield in a subtropical region. *Hydrol. Process.* **2014**, *28*, 2671–2684. [\[CrossRef\]](#)
35. Faye, B.; Du, G.; Li, Q.; Sané, T.; Mbaye, E.; Zhang, R. Understanding the characteristics of agricultural land transition in Thiès region, Senegal: An integrated analysis combining remote sensing and survey data. *Front. Environ. Sci.* **2023**, *11*, 1124637. [\[CrossRef\]](#)
36. Faye, B.; Du, G.; Mbaye, E.; Liang, C.; Sané, T.; Xue, R. Assessing the Spatial Agricultural Land Use Transition in Thiès Region, Senegal, and Its Potential Driving Factors. *Land* **2023**, *12*, 779. [\[CrossRef\]](#)
37. Nasiakou, S.; Vrahnakis, M.; Chouvardas, D.; Mamanis, G.; Kleftoyanni, V. Land Use Changes for Investments in Silvoarable Agriculture Projected by the CLUE-S Spatio-Temporal Model. *Land* **2022**, *11*, 598. [\[CrossRef\]](#)
38. Chasia, S.; Olang, L.O.; Sitoki, L. Modelling of land-use/cover change trajectories in a transboundary catchment of the Sio-Malaba-Malakisi Region in East Africa using the CLUE-s model. *Ecol. Modell.* **2023**, *476*, 110256. [\[CrossRef\]](#)
39. Guo, A.; Yue, W.; Yang, J.; Xue, B.; Xiao, W.; Li, M.; He, T.; Zhang, M.; Jin, X.; Zhou, Q. Cropland abandonment in China: Patterns, drivers, and implications for food security. *J. Clean. Prod.* **2023**, *418*, 138154. [\[CrossRef\]](#)
40. Yuan, H.; Chen, Y.; Lin, J.; Zhang, Y.; Zhu, C. Analysis of the spatial differentiation and driving force of arable land abandonment and non-grain in the hilly mountainous areas of Gannan. *Heliyon* **2024**, *10*, e33481. [\[CrossRef\]](#) [\[PubMed\]](#)
41. Jiang, G.; Ma, W.; Li, Y.; Zhou, D.; Zhou, T. Mapping Abandoned Cultivated Land in China: Implications for Grain Yield Improvement. *Appl. Sci.* **2024**, *15*, 165. [\[CrossRef\]](#)
42. Huang, M.; Li, Y.; Ran, C.; Li, M. Dynamic changes and transitions of agricultural landscape patterns in mountainous areas: A case study from the hinterland of the Three Gorges Reservoir Area. *J. Geogr. Sci.* **2022**, *32*, 1039–1058. [\[CrossRef\]](#)
43. Ke, S.; Cui, H.; Lu, X. GeoDetector analysis of spatio-temporal patterns and driving mechanisms of farmland spatial transition within 897 counties in the Yangtze River Economic Belt, China. *Humanit. Soc. Sci. Commun.* **2025**, *12*, 923. [\[CrossRef\]](#)
44. Fayet, C.M.J.; Reilly, K.H.; Van Ham, C.; Verburg, P.H. What is the future of abandoned agricultural lands? A systematic review of alternative trajectories in Europe. *Land Use Policy* **2022**, *112*, 105833. [\[CrossRef\]](#)
45. Xie, H.; Zhang, Y.; Choi, Y. Measuring the Cultivated Land Use Efficiency of the Main Grain-Producing Areas in China under the Constraints of Carbon Emissions and Agricultural Nonpoint Source Pollution. *Sustainability* **2018**, *10*, 1932. [\[CrossRef\]](#)
46. Li, S.; Li, X.; Sun, L.; Cao, G.; Fischer, G.; Tramberend, S. An estimation of the extent of cropland abandonment in mountainous regions of China. *Land Degrad. Dev.* **2018**, *29*, 1327–1342. [\[CrossRef\]](#)
47. Zhang, M.; Li, Q.; Faye, B.; Yang, A. Unveiling the Spatiotemporal Drivers of Green Utilization Efficiency of Cultivated Land in China: A PEST-GTWR Framework. *Land* **2025**, *14*, 2329. [\[CrossRef\]](#)

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.