

Article

Analysing the Spatial and Temporal Characteristics of Ecological Land Encroachment by Cropland Expansion and Its Drivers in Cambodia

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Abstract: The rapid expansion of cropland in Cambodia, the world's seventh-largest rice exporter, has created an imbalance in land use structure. However, there is a lack of quantitative investigation of the loss of ecological land as a result of the expansion of cropland and its drivers. In this research, spatial autocorrelation, landscape pattern index and transfer matrix methods were used based on land use data from 2000 to 2023. Then, the eXtreme Gradient Boosting-SHapley Additive exPlanations (XGBoost-SHAP) and Geographic Detector were used to explore the drivers of cropland expansion. The findings indicate that the expanse of agricultural land in Cambodia has significantly increased by 13.47%. The proportion of cropland to the land area (37.87%) is close to that of forest (40.19%). Cultivated land is dominated by rice fields, supplemented by drylands. Spatial clustering is obvious in both drylands and rice fields. Drylands are mainly concentrated in the eastern and western mountainous areas and the northern border, while rice fields are concentrated in the central plains. Cultivated land encroached on a total of 30,579.27km² of ecological land, of which 62.88% was dry land and 37.12% was rice fields. Forests and shrubs are the main source of expansion of cropland. In addition, soil type (0.18), elevation (0.17) and GDP (0.17), population (0.52) and their interactions strongly drove the expansion of dryland and rice fields. Cambodia should conduct scientific research to assess the demand for cropland by population growth and economic progress. It should realize the orderly growth of cultivated land, reduce the damage to ecological land, and promote the coordinated development of society, environment and economy.

Keywords: Cambodia; cropland expansion; ecological land use; drivers



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1. Introduction

As an essential resource for sustaining and advancing human life, cropland is not only the foundation for food security and agricultural production but also a key vehicle for biodiversity conservation and ecosystem services [1,2]. However, the global rate of cropland expansion has almost doubled in the past two decades, and tropical regions in particular are facing more serious problems of cropland expansion [3,4]. The speedy increase in arable land has contributed to the extensive disappearance of natural environments, including forests and wetlands [5,6]. This threatens not only global biodiversity but may also lead to a decline in ecosystem services [1,7,8]. In addition, the expansion of cropland is often accompanied by irrational agricultural practices. For instance, over-tillage and the indiscriminate use of chemical fertilisers and pesticides have further exacerbated soil degradation and ecological damage [9–11]. Hence, exploring the expansion of cropland and the factors behind it in tropical regions is essential for land conservation and achieving sustainable use of land resources.

Cambodia is a typical tropical agricultural country where farming constitutes the predominant livelihood, with more than three quarters of the population dependent on it [12]. Fertile land, a dense river network, and an abundant rural labour force give it significant potential for agricultural development. The structure of Cambodia's cropland is dominated by lowland rice fields, supplemented by upland dryland cultivation [13,14]. Cambodia's cropland has expanded significantly in recent decades, notably in the expansion of rice fields from 2000 to 2020 [15,16]. However, this expansion has brought about a reduction in the extent of ecological land, such as forests and wetlands. For example, Cambodia's forest cover declined from 59.09% in 2006 to 46.86% in 2018 [17]. This change not only affects biodiversity but also threatens the country's ecological security and agricultural productivity. Cambodia is in a crucial phase of growing population and economic progress, where the swift expansion of cropland may lead to a range of environmental problems. The challenge now is how to meet food and economic needs while minimising environmental impacts through rational management of cropland. Faced with this challenge, the government of Cambodia is endeavoring to find a middle ground between fostering economic growth and upholding environmental integrity. Important policies, for instance, the draft National Agricultural Development Policy (2022–2030), have been proposed to promote the modernisation of agriculture and international competitiveness [18]. Existing studies have mainly focused on spatial and temporal changes in land use types or changes in forest areas in Cambodia but have not yet paid attention to the encroachment of its ecological land by the expansion of cropland [15,16,19]. Therefore, it is imperative to map the spatial and temporal changes in Cambodia's cropland and its relationship with ecological land types like forests and wetlands. This will contribute to an in-depth understanding of land-use conflicts and resource competition mechanisms and provide a reliable scientific basis for policy formulation.

Cropland expansion is a global phenomenon, and its drivers are complex and varied, involving natural conditions, socio-economics, and policies [20–22]. An in-depth discussion of the driving mechanisms of arable land expansion is important for effectively curbing uncontrolled expansion and mitigating the negative impacts on terrestrial ecosystems. In regard to the selection of influencing factors, existing studies mainly focus on the intensity of the influence of natural elements (topography, temperature, precipitation, etc.) and human factors (population expansion, economic development and policies and regulations) on the expansion of cropland. With regard to natural factors, conditions such as topography [23,24], precipitation [25,26], and soil type [27] play a direct role in influencing the suitability of cropland. The dynamics of cropland expansion are also exacerbated by changes in planting seasons and crop growing conditions due to climate change [28,29]. In terms of human factors, population growth [30,31], increasing Gross Domestic Product (GDP) [32,33], and rising market demand [1,34] are important drivers of cropland expansion, especially in less economically developed regions. In addition, road accessibility and ease of access to markets have put more natural areas under pressure to develop cultivated land [35,36]. At the same time, policy guidance and government support are crucial in driving this process. In particular, the construction of the Funan Techo Canal will enhance the accessibility of the region, which may further boost the market demand for agricultural products and the development of cropland in the future [37]. Therefore, in this paper, eight factors (elevation, slope, slope direction, temperature, precipitation, GDP, population and soil type) are selected as the influencing factors for the expansion of cropland, combining with the actual situation of Cambodia and the existing researches. In terms of impact factor assessment methods, the existing methods for analysing the drivers of cropland expansion mainly include traditional methods such as Pearson correlation coefficient [38], Logistic regression model [39], partial least squares regression [40], geographically weighted regression [41], and geographical detector [42]. Among them, geographical detector have been used in different scale regions due to their ability to explore single and multi-factor interactions [33,43,44]. Although traditional methods have

been widely used in exploring the drivers of land use change, they have some limitations in dealing with the complex relationships between the drivers. Machine learning methods exhibit significant advantages over traditional approaches in analysing land use change drivers, especially in dealing with non-linear relationships [45,46]. Among them, the eXtreme Gradient Boosting (XGBoost) algorithm shows significant advantages due to its high accuracy, regularisation to prevent overfitting, and ability to perform multi-scale analysis [47]. This makes it a powerful tool for understanding and predicting land use change. SHapley Additive exPlanations (SHAP) is a unified method for interpreting the output of any machine learning model. It is capable of visualising and describing complex causal relationships between drivers and predictive goals [48]. XGBoost combined with SHAP can analyse the driver relationships hidden in the XGBoost black-box model [49]. Thus, it helps researchers to deeply understand the complex causal relationships of land use change. For example, Lu et al. used the XGBoost-SHAP model to explore the drivers of terrace abandonment in China [50]. Zhang et al. used the same model to explore the drivers of cropland de-farming in some regions of China [51]. Recently, Cambodia's rapid economic growth and urbanization have further intensified cropland expansion. Niu et al. highlight that key factors driving land use change in Cambodia include agricultural value-added, exports of raw agricultural materials, urban population growth, and urbanization rates [15]. However, existing research is still insufficient on the drivers of cropland change in Cambodia. Cropland expansion is usually regarded as a result of forest decline, and there is a lack of quantitative analysis of the contribution of natural and socio-economic factors and their interactions to cropland expansion [15,52,53]. Therefore, in this study, the XGBoost-SHAP model and geographical detector model were used to explore the effects of single factor and multi-factor interactions on the expansion of cropland in Cambodia, respectively.

In summary, this study used land use data from 2000–2023 and employed the rate of cropland change, land use transfer matrix, landscape pattern index, and spatial autocorrelation methods. The spatial and temporal changes of cropland and its encroachment on ecological land in Cambodia from 2000–2023 were explored at quantitative, structural, and landscape scales. In addition, the drivers of cropland expansion in Cambodia from 2000–2019 were explored using the XGBoost-SHAP and geographical detector model based on natural and socio-economic data. The study's findings not only shed light on the complexities of cropland changes and their driving factors, but also offer scientific evidence and decision-making support for responding to climate change, guaranteeing food security, and promoting sustainable agricultural development.

2. Study Area and Data Sources

2.1. Study Area

Cambodia is located between 10° N–15° N and 102° E–108° E, with a total area of about 180,000 km². The region has a tropical monsoon climate with high temperatures and rainfall throughout the year, divided into rainy and dry seasons. Its topography is characterised by a low-lying centre surrounded by highlands and mountains. The central area is a fertile Mekong alluvial plain, which provides rich agricultural resources and good natural conditions for agricultural development. The type of land use in Cambodia is mainly dominated by cropland and forests, of which forests and cropland account for 38.78% and 40.19%, respectively (excluding economic forests) (Figure 1a,b). In recent years, Cambodia's economic progress has been strong and the population has shown a rapid growth trend.

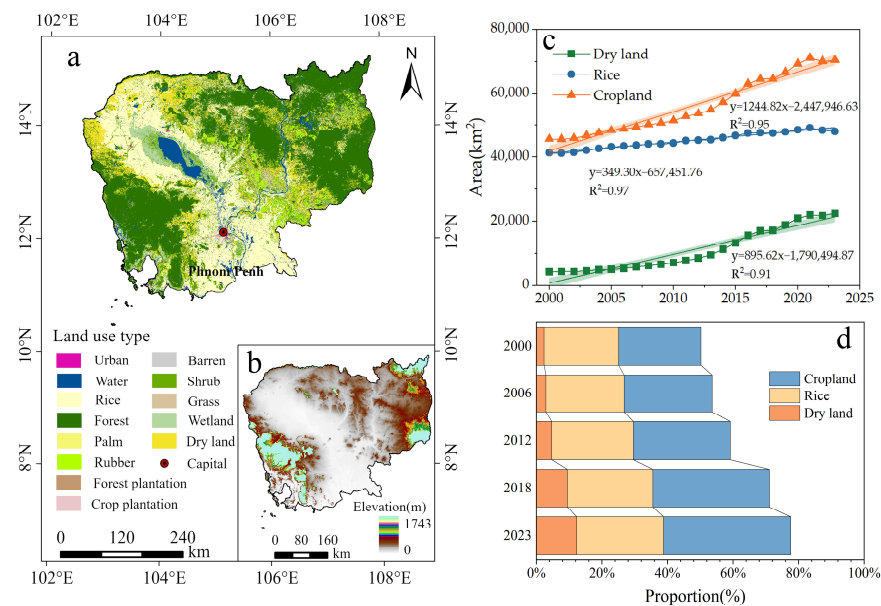


Figure 1. (a) is a map of land use types in Cambodia. (b) is a map of elevation in Cambodia. (c) is a map of the trend of the area of cropland, dryland and rice fields in Cambodia from 2000 to 2023. (d) is a map of the proportion of cropland, dryland and paddy to the total area of Cambodia from 2000 to 2023.

2.2. Data Sources and Processing

This study utilized land use, climatic, topographic, and socio-economic data. The land use data were collected from the Regional Land Cover Monitoring System (RLCMS) (<https://www.landcoverMapping.org/>, accessed on 2 November 2024) with a spatial resolution of 30 m [54]. The dataset includes 19 land use types, including cropland, forest plantations, rubber, etc. The study selected the data from 2000 to 2023 and processed the data by projection, cropping, and reclassification to get 13 types of land use types in Cambodia. Among them, the land use types other than impervious surface and cropland were defined as ecological land [55]. Administrative boundary data were obtained from the Global Administrative Boundaries Database (<https://gadm.org/>, accessed on 2 November 2024), which provides data on administrative boundaries at three levels for individual countries and territories around the world. Temperature and precipitation data were sourced from the ERA5-Land monthly averaged data at the Copernicus Meteorological Data Repository (<https://cds.climate.copernicus.eu/>, accessed on 1 November 2024) at a resolution of $0.1^\circ \times 0.1^\circ$. From these, 2-meter temperature and total precipitation data for 2000–2019 were selected, and the mean annual temperature and total annual precipitation for Cambodia were calculated based on the official description files. The DEM data were obtained from the USGS (<https://earthexplorer.usgs.gov/>, accessed on 2 November 2024) Shuttle Radar Topography Mission (SRTM) 90-meter digital elevation data (SRTM90_v4) from which slope and aspect data were extracted. GDP data for 2000–2019 were derived from the global 1 km $\times$ 1 km real gross domestic product for 1992–2019 (<https://doi.org/10.6084/m9.figshare.17004523.v1>, accessed on 3 November 2024) [56]. Population data were derived from World Pop (<https://hub.worldpop.org/>, accessed on 2 November 2024) at 1 km resolution. Soil type data was obtained from Open Development Cambodia (<https://opendevelopmentcambodia.net/>, accessed on 3 November 2024) and includes 17 soil types.

3. Research Methodology

3.1. Rate of Cropland Change

The rate of cropland change can quantitatively reflect the annual variation in cropland within a specific time frame and serves as a key indicator for assessing shifts in cropland

resources. The higher the rate of cropland change, the faster the regional cropland changes, indicating lower stability in the cropland. Conversely, a lower rate of change suggests better stability of cropland [2]. The rate of cropland change was calculated for five periods with an interval of six years. The calculation formula is:

$$D = \frac{S_{t2} - S_{t1}}{S_{t1}} \times \frac{1}{T} \times 100\% \quad (1)$$

where D is the rate of cropland change. S_{t1} and S_{t2} are represent the cropland area at the start and end of the study, and T denotes the study duration.

3.2. Spatial Autocorrelation

Spatial autocorrelation is a method for analyzing the distribution patterns of geographic phenomena, which is used to detect the degree of aggregation and similarity of spatial data in geographic space. Spatial autocorrelation analysis can be classified into global and local types [57]. In this paper, these two methods are used to measure the characteristics of the spatial pattern of cropland in the study area.

$$I = \frac{n \sum_{i=1}^n \sum_{j=1}^n w_{ij} (x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^n \sum_{j=1}^n w_{ij} \sum_{i=1}^n (x_i - \bar{x})^2} \quad (2)$$

$$I_i = \frac{n(x_i - \bar{x})}{\sum_{i=1}^n (x_i - \bar{x})^2} \sum_{i=1}^n w_{ij} (x_j - \bar{x}), (i \neq j) \quad (3)$$

where I is the global Moran's index, I_i is the local Moran's index, n is the number of data, x_i and x_j is the observed value of the region i and j , $\bar{x}$ is the average value of the whole domain, and w_{ij} is the spatial weight of i and j .

3.3. Land Use Transfer Matrix

Land use transfer matrix can reveal the direction and magnitude of changes in each land use type across different periods, allowing for a quantitative description of land use transitions [58]. In this study, using land use data from 2000 to 2023 with ArcGIS Pro 3.1, the land use transfer matrix was generated for the periods 2000–2006, 2006–2012, 2012–2018, and 2018–2023. Its calculation formula is:

$$P = \begin{Bmatrix} A_{11} & A_{12} & \cdots & A_{1n} \\ A_{21} & A_{22} & \cdots & A_{2n} \\ \vdots & \vdots & A_{ij} & \vdots \\ A_{n1} & A_{n2} & \cdots & A_{nn} \end{Bmatrix} \quad (4)$$

where A represents the area of the land class. i and j represent the land classes at the at the beginning and conclusion of the study, respectively, and n refers to the number of land classes.

3.4. Landscape Pattern Index

The landscape pattern index reflects the composition and spatial arrangement of the landscape's ecological structure. We chose patch density (PD), mean patch area (MPA), and edge density (ED) to reflect the degree of fragmentation, distribution density, and scale size of cropland [3,59]. Based on the ArcgisPro3.1 platform, we generated a 5 km × 5 km grid, and used the R language to generate landscape indices for ecological land in 2000, 2012, and 2022, respectively.

3.5. Trend Analysis

Trend analysis predicts the future direction of variables over time through linear regression [60]. In this study, we conducted a trend analysis of PD, ED and AREA_MN for ecological land in order to better quantify the encroachment of cropland into ecological land.

$$Slope = \frac{n \sum_{i=1}^n (i \times F_i) - \sum_{i=1}^n i \times \sum_{i=1}^n F_i}{n \sum_{i=1}^n i^2 - (\sum_{i=1}^n i)^2} \quad (5)$$

where *Slope* is the slope of the like element regression equation, F_i is the mean value of the fragmentation index in year i , and n is the study duration. A positive Slope (>0) reflects an upward trend, a Slope of 0 indicates stability, and a negative Slope (<0) represents a downward trend.

3.6. Analysis of the Drivers of Cropland Change

3.6.1. Exploration of Single Factor Drivers

We used the XGBoost algorithm combined with the SHAP method to improve the transparency and interpretability of model predictions. SHAP values quantify how much each feature contributes to the model's predicted results. Thereby, it helps us to understand the influence of factors such as climate, socio-economics and topography on changes in cropland area. Using the PyCharm platform, we divided the dataset into a 70% training set and a 30% testing set. And we optimised the hyperparameters of the XGBoost model by setting *n_estimators* to 1000 and *learning_rate* to 0.13 to get the best model performance. In addition, we implemented 10-fold cross-validation to assess the stability and accuracy of the model [50,51]. Nevertheless, our analyses only cover up to 2019 due to the temporal resolution limitations of GDP data.

3.6.2. Multifactor Interaction Exploration

Geographical detectors identify spatial disparities and their drivers by discretising data, extracting attributes, analysing detections and interpreting results [61]. This reveals the causes of interregional differences and the spatial distribution of risk areas. This study is based on the "GD" package in R to investigate the impact of the interaction of natural and anthropogenic factors on the expansion of cropland in Cambodia.

4. Results

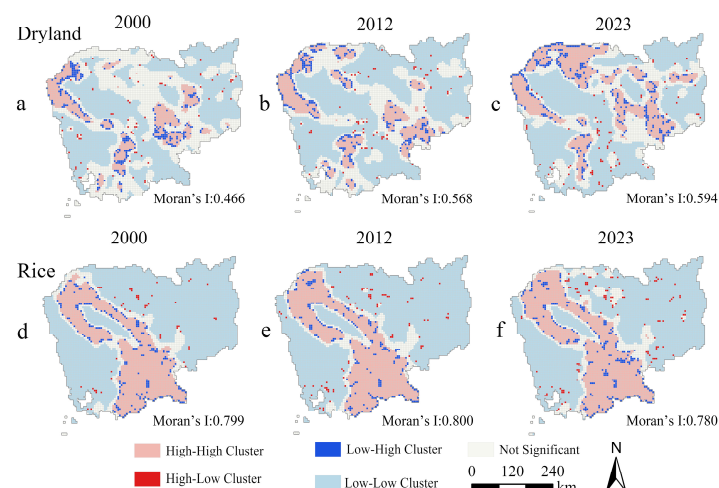
4.1. Changes in the Amount of Cropland and Spatial Distribution Patterns

Cambodia is mainly dominated by cropland and forests, and the changes in cropland are drastic. In terms of quantity, Cambodia's cropland area has experienced a significant growth over the 23-year period, expanding by a total of 26,865.08 km². The proportion of cropland (including dry land and rice fields) in the national land area has increased from 25.31% in 2000 to 38.78% in 2023, with an increase of 13.47%. The proportion of cropland in the national territory is gradually approaching the proportion of forests (40.19%), and the area of cropland is fast approaching the area of forests (excluding plantation forests such as palm, rubber, etc.) (Figure 1c,d). In terms of structure, cropland is mainly dominated by rice fields, supplemented by drylands, with the changes in drylands being greater than those in rice fields. The areas of drylands and rice show an increasing trend, with their share increasing from 2.37% and 22.73% in 2000 to 12.34% and 26.44% in 2023, with an increase of 9.97% and 3.71%, respectively. In terms of the rate of cropland change, the rate of cropland change reaches 9.74%, with a strong change in area. Dryland change fluctuated considerably, with 2012–2018 being the period of highest change in dryland, with change as high as 16.66%. The rate of rice fields change, on the other hand, is more stable, with the rate of change remaining between 0.70% and 0.85% from 2000–2018, with a slow and stable change in area. The rate of change of both dryland and rice shows a decline from 2018–2023 (Figure 1, Table 1).

Table 1. Changes in cropland area (km² and percentage).

Year	Change Type	Cropland	Dryland	Rice
2000–2006	Area change	3143.79	1045.14	2098.65
	% change	1.15	4.05	0.85
2006–2012	Area change	5046.19	3227.21	1818.98
	% change	1.77	10.06	0.7
2012–2018	Area change	10,814.99	8568.73	2246.27
	% change	3.37	16.66	0.83
2018–2023	Area change	5853.06	5278.21	574.85
	% change	1.9	6.16	0.24
2000–2023	Area change	24,858.04	18,119.3	6738.74
	% change	9.74	1.91	0.71

From the spatial point of view, Cambodia's cropland shows a symmetrical spatial pattern. With Tonle Sap Lake as the centre, the farmland shows a distribution pattern of “rice fields—dry land” from inside to outside (Figure 1a). The global Moran's I index reveals that both drylands and rice fields in Cambodia show obvious spatial clustering characteristics. The spatial clustering of rice fields is significantly higher than that of drylands, and its clustering is maintained at a high level, showing a more stable spatial distribution trend. On the other hand, the spatial clustering of drylands shows a steady increasing trend. Local autocorrelation analyses further revealed that four main spatial clustering patterns were formed in Cambodia's drylands and rice fields: low-low clustering, low-high clustering, high-high clustering, and high-low clustering (Figure 2). The spatial clustering patterns of drylands and rice paddies in Cambodia changed significantly from 2000 to 2023. The area of both the high-high and low-high clustering of drylands increased significantly, with the addition of mountainous areas on the eastern side of the Tonle Sap Lake basin and a small increase on the western side (Figure 2a,b). In contrast, the high-high clustering and low-high clustering of rice fields were more stable and mainly distributed in the central plains. Among them, the high-high clustering had a small increase in the northern region bordering Thailand, while the low-high clustering showed a clear increasing trend on the eastern side of the Tonle Sap Lake (Figure 2d–f).

**Figure 2.** Localized spatial autocorrelation distributions in dryland and rice fields. (a–c) are drylands, (d–f) are rice fields.

4.2. Encroachment of Cropland on Ecological Land Use

We screened the paths of encroachment of cropland on various types of ecological land, excluding those land categories where the proportion of encroached area to total area was less than 0.1%. We then analyzed only those land categories where the proportion was greater than 0.1%. We found that a total of 30,579.27 km² of ecological land was encroached

on by cropland over a period of 23 years, of which 19,229.73 km² was encroached on by drylands and 11,349.53 km² was encroached on by rice fields. Two ecological land types, forests and shrubs, are the main sources of dryland and rice field expansion. Drylands encroach on 16,587.15 km² of forests, accounting for about 81.67% of their total encroachment. Meanwhile, rice fields encroached on 5530.67 km² of forest, accounting for 45.37% of its total encroachment. Drylands and rice fields encroached on 1727.69 km² and 2442.16 km² of shrubs, accounting for 8.51% and 20.04% of their total encroachment, respectively (Figure 3e). The performance of dryland and rice field expansion showed some differences in different periods. The encroachment of drylands on forests initially increases and then decreases. During the period 2000–2006, forest encroachment was the smallest, with an area of 1352.09 km². The peak of encroachment was in 2012–2018, with an encroachment area of 5728.40 km², while in 2018–2023, the encroachment of forests decreased slightly to 5684.55 km². In contrast, encroachment of rice on forests shows a continuous upward trend. In particular, rice field encroachment on forest reaches its maximum value of 1292.30 km² in 2018–2023. For shrub encroachment, both drylands and rice fields initially show an increase, which is later followed by a decline. During the period 2000–2018, dryland and rice field encroachment on shrubs generally showed an increasing trend. However, in 2018–2023, dryland and rice field encroachment on shrubs decreased by 308.35 km² and 427.38 km², respectively, compared to the period 2012–2016 (Figure 3a,b).

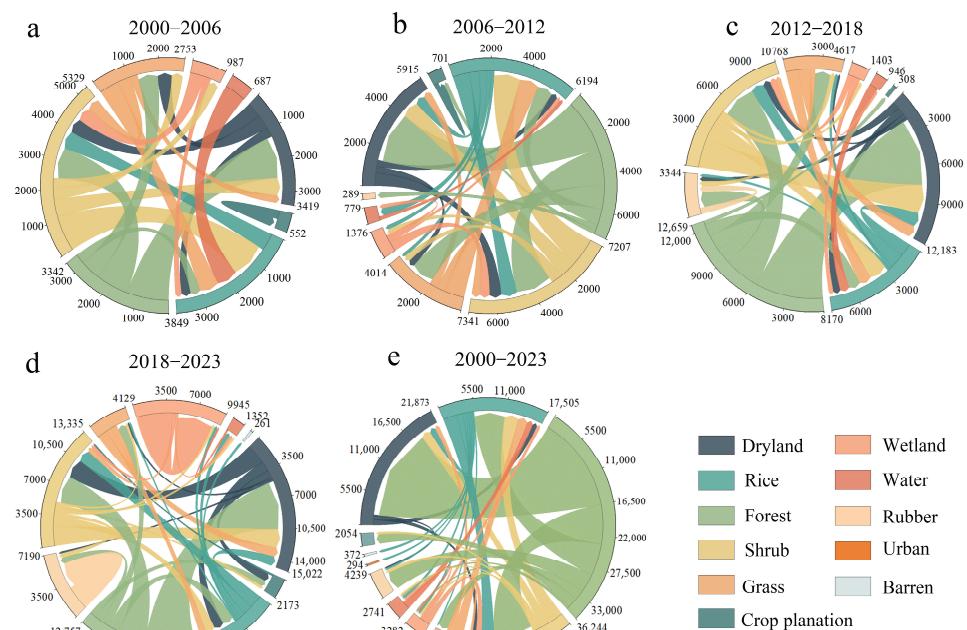


Figure 3. Ecological land use map of cropland encroachment in Cambodia, 2000–2023.

4.3. Analysis of Ecological Land Fragmentation Due to Cropland Encroachment

Analysed by the landscape pattern index, the expansion of cropland significantly exacerbated the fragmentation of ecological land. The PD of ecological land showed a fluctuating upward trend as the area of dryland and rice fields increased (Figure 4g). The PD of ecological land in the east, west, and downstream areas of Tonle Sap Lake showed an increasing trend, especially in the ecological land in the eastern mountain area. Overlaying the trends of cropland and ecological land use, it was found that the areas of increased ecological land use PD were mainly located around the distribution of dryland and rice fields (Figure 4a,b). In terms of ED, the ED of ecological land has gradually increased with the expansion of dryland and rice field areas, and the increase in ED has led to a further increase in the degree of fragmentation (Figure 4h). The area of increase in ED is mainly concentrated in the Tonle Sap Lake Basin and its eastern region.

Similarly, overlaying the distribution maps of drylands and rice fields reveals that the areas of increased ecological land use ED are mostly located around the distribution of drylands and rice paddies (Figure 4c,d). Regarding the AREA_MN, the AREA_MN of ecological land use shows a significant decreasing trend as the area of dryland and rice grows and exhibits a gradual decrease in spatial distribution (Figure 4i). Overlay analyses showed that the peripheral areas of drylands and rice fields were almost all located within the area of declining ecological land AREA_MN (Figure 4e,f).

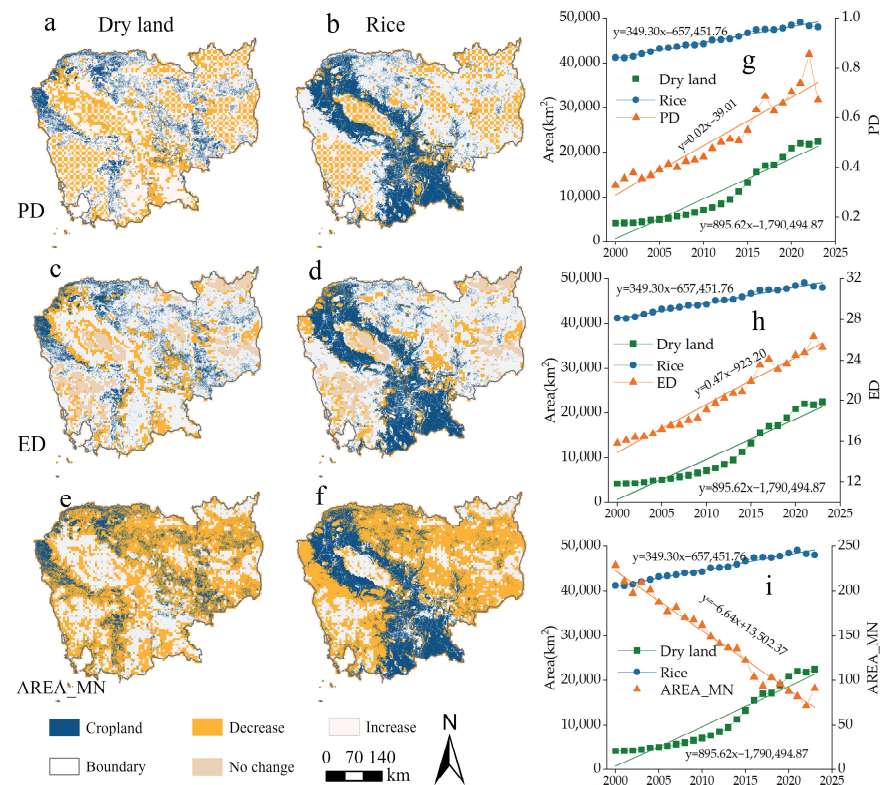


Figure 4. (a–f) are superimposed graphs of the spatial distribution of cropland and the results of the trend analysis of the landscape pattern index of ecological land, respectively. Among them, (a,c,e) and (b,d,f) are dryland and paddy field, respectively. (g–i) are graphs of changes in the landscape pattern index versus the area of dryland and paddy field, respectively. PD represents patch density, edge density, ED represents edge density, average patch area AREA_MN represents average patch area.

4.4. Analysis of the Drivers of Cropland Expansion

Changes in croplands are affected by multiple natural and economic influences. In this paper, eight factors (temperature, precipitation, soil type, elevation, slope, aspect, population, and GDP) were selected from both natural and socio-economic aspects in the context of the study area. Then, the contribution of each factor and their interactions to the change of dryland and rice field areas was explored. From the single-factor point of view, the R^2 of the XGBoost-SHAP model for dryland and rice fields was 0.73 and 0.94, respectively, which was a better fit and a more explanatory model. Regarding natural factors, the expansion of dryland area is mainly limited by soil type, which contributes a rate of 0.18. In addition, the contribution of altitude to dryland change is also high, at 0.16. For anthropogenic factors, drylands are mainly driven by economic development, with GDP contributing as much as 0.17. Population and rainfall also play a significant role in dryland area changes, with contribution rates of 0.13 and 0.12, respectively (Figure 5a). For rice paddies, elevation is the main natural factor affecting paddy expansion with a contribution of 0.17. Population growth was the most significant anthropogenic factor contributing to its area change, with a contribution of 0.52. Precipitation and soil type followed with a contribution of 0.09 and 0.08, respectively (Figure 5b).

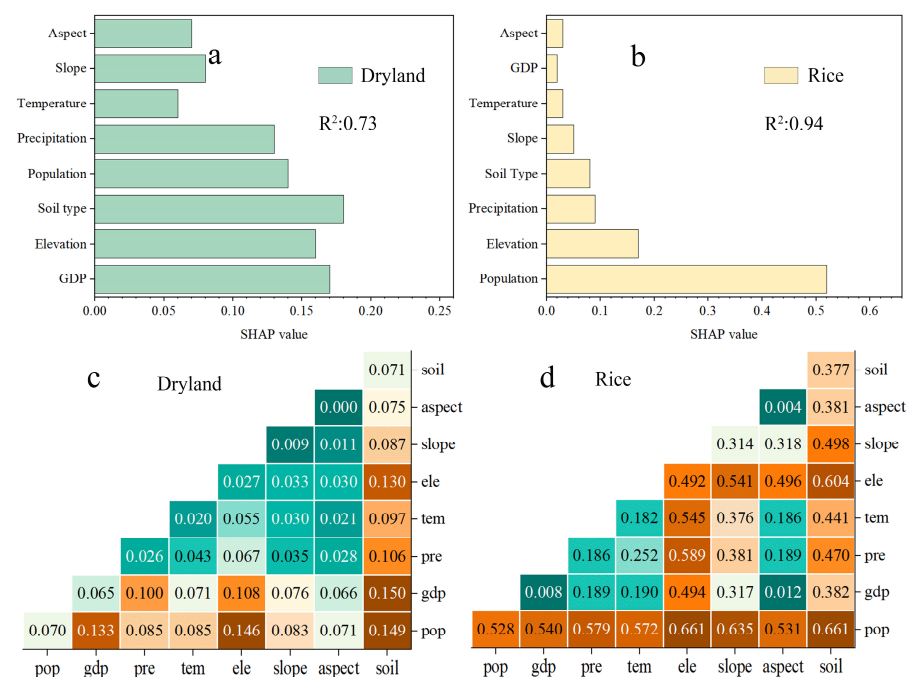


Figure 5. Contribution of factors to changes in dryland and rice fields areas. (a,b) are the extent to which a single factor drives dryland and paddy fields, and (c,d) are the extent to which each factor interacts to drive dryland and rice fields. pop represents the population, GDP represents the Gross Domestic Product, ele represents the elevation, pre represents the precipitation, and tem represents the temperature.

Regarding the multifactor interactions, the interactions between the factors in both dryland and rice fields drove the changes in cropland to a stronger extent than the single factors. For drylands, the interaction between GDP and soil type was the strongest for dryland expansion at 0.150. The interaction between population and soil type was the next strongest at 0.149. The interaction between elevation and population is also stronger at 0.146 (Figure 5c). In the case of paddy fields, the strength of the effect of the interaction of elevation and population and elevation and soil type on rice fields expansion was consistent at 0.661. The interaction of slope and population was the next strongest at 0.635. In addition, the interaction of soil type and elevation was also stronger at 0.604 (Figure 5d).

5. Discussion

5.1. Characteristics of Spatial and Temporal Changes in Cropland Expansion

In analysing the trend of cropland change in Cambodia over the period 2000–2023, we observed a significant increase in the area of dryland and rice fields. This trend is consistent with the findings of Niu et al., who also noted a significant increase in the area of rainfed and irrigated farmland [15]. Based on a comparison of the available literature, we find that the phenomenon of cropland expansion in Cambodia is a regional problem in Southeast Asia. The study noted that except for Thailand, where agricultural expansion slowed down after 2000, Myanmar, Laos, and Vietnam all showed an upward trend in agricultural expansion from 1987–2018 [62,63]. Meanwhile, the Amazon region, which is also a tropical region with Cambodia, also maintains an increasing trend in agricultural land area between 2000 and 2020 [64]. In addition, recent global studies have shown that cropland is increasing globally with an accelerating trend of expansion, especially in the tropics [4,65]. The study by Liu et al. points to a remarkable trend of net annual increase in global cropland area since 2000, with an average annual increase of $1.9 \times 10^4 \text{ km}^2$ [66]. Therefore, the expansion of cropland is not only a regional but also a global problem. We found that the rate of increase in dryland area peaked between 2012 and 2018, and encroachment on forests and shrubs was also highest during this period. This may be due to a combination of

factors such as changes in agricultural policy, increased market demand, and the impact of climatic conditions. For example, Cambodia's economic land concession policy significantly accelerated dryland expansion, resulting in large-scale loss of forests and shrubs [67]. In addition, according to previous studies, Cambodia experienced severe droughts during that period, and more farmers may have compensated for the economic losses by continuously expanding their production area [68,69]. In contrast, the smaller change in rice field area may be related to the higher dependence of rice fields on water resources. The expansion of rice fields may be limited by the construction of irrigation facilities and the capacity of water management [70,71]. Moreover, we also found that the spatial clustering of drylands and rice fields is very significant. Rice fields are mainly concentrated around Tonle Sap Lake and downstream in water-rich areas. Drylands, on the other hand, are concentrated in the mountainous areas to the east and west, with less demand for water resources. This suggests that natural conditions have somewhat limited changes in rice fields. It is worth noting that the rate of change in both dryland and rice fields declined during 2018–2023, and encroachment on ecological land also showed a decreasing trend. This trend may stem from the combined effects of rising national awareness of environmental protection, improved technology, and adjustments in agricultural policies [72,73]. In addition, our study found that the fragmentation of ecological land in areas closer to cropland and rice paddies is increasing, and that increased fragmentation has an immeasurable impact on the environment. Earlier research have identified the expansion of cropland and permanent crops as the main cause of forest loss in Cambodia, with agricultural expansion accounting for about 17% of the total loss of forests in Mainland Southeast Asia [62,74]. Large-scale expansion of cropland has not only led to a substantial loss of forests and shrublands, but has in turn had an impact on ecosystem functioning. For example, biodiversity is reduced and carbon storage capacity is weakened [65,75]. In addition, these changes may trigger wider environmental issues, including exacerbating global climate change and affecting the stability of regional climates [75,76]. Thus, the encroachment of cropland on ecological land not only affects the local ecological balance but may also have a knock-on effect on the global environment. In this context, the Ministry of Environment of Cambodia, in its Circular Strategy on Environment 2023–2028, has set the goal of increasing the national forest cover to 60% by 2050 [77]. Increased awareness of environmental protection, accelerated urbanisation, development of the non-agricultural sector, and rising economic levels may prompt more land to be converted to non-agricultural use. At the same time, technological advances in agriculture are likely to further increase crop yields, thereby alleviating the need for expansion of agricultural land.

5.2. Exploring the Driving Mechanisms of Cropland Expansion

This paper analyses the drivers of dryland and rice field area changes in Cambodia between 2000 and 2019 using the XGBoost-SHAP and Geographical Detector models. GDP and population are the dominant anthropogenic factors for dryland and rice field change in Cambodia, respectively. However, studies by Niu et al. and Soum et al. on national and provincial scale land use change in Cambodia point out that population and economic growth significantly drive land change in Cambodia, which is consistent with the results of this study [15,16]. Yet the influence of natural factors on the expansion of cropland has not been explored. Focusing on regional and global inquiries, most have explored the role of population and economic development in driving the expansion of cropland. For example, in studies on the expansion of cropland in Nanfu, Thailand, as well as in the uplands of Southeast Asia, it was noted that market demand, and the need for economic development drove the expansion of cropland [6,78]. Potapov et al. also mentioned that population drives the expansion of cropland in their study of global cropland change [4]. As a large agricultural country, Cambodia faces the dual pressure between economic progress and food demand. Demand for agriculture driven by economic growth will further drive the expansion of cultivated land. However, population growth is likely to prompt more land to be used for food production in order to meet basic food needs. During the period from

2000 to 2019, as Cambodia gradually transitioned from post-war economic reconstruction to a phase of rapid development, agriculture played an important role in supporting economic growth and food security, becoming the country's economic mainstay [53]. Rice is the staple food crop in Cambodia, and the area under its cultivation has increased in line with population growth. In addition, maize and cassava are the main crops grown in the drylands of Cambodia. In 2020, Cambodia introduced the National Cassava Policy 2020–2025, which aims to establish Cambodia as a production, processing, and supply base for sustainable cassava products to meet global and regional market demand [79]. The implementation of this policy may further contribute to the expansion of cassava cultivation, thus affecting changes in the area of drylands. In this research, we explore the extent to which natural factors drive the expansion of cropland. We found a significant effect of soil type and elevation on cropland expansion. Low-altitude areas are more suitable for rice cultivation, and rice fields are mainly concentrated in the central plains of Cambodia, which have better irrigation conditions and soil fertility. In contrast, higher altitudes are favoured for dryland crops such as maize and cassava, which require less water and are adapted to a wide range of climatic conditions. Soil type also influences crop selection and yields, with rice growing in fertile soils with good water retention. Cassava and maize can be grown in poor soils. Our study found that the interaction of soil type with GDP had the strongest effect on the expansion of dryland area. Whereas the interaction of elevation with population and soil type had a stronger effect on the expansion of paddy fields. It suggests that the expansion of cropland is the result of a combination of natural and anthropogenic factors. In addition, Rainfall patterns are critical to agricultural activities, as Cambodia has a distinct rainy and dry season, and the spatial and temporal distribution of rainfall directly affects crop growth cycles and yields. Dryland crops are highly drought-tolerant, while rice requires a stable water supply. Policy decisions may also affect changes in cultivated land. For example, the construction of the Funan Techo Canal has improved transport conditions, which may contribute to the expansion of arable land in the short term. However, in the long term, industrial diversification may lead to a shift of labour to sectors such as logistics, which may inhibit the expansion of arable land to some extent. Natural factors determine the suitability of cropland for cultivation, while anthropogenic factors determine the amount of cropland expansion, and together they drive cropland expansion.

5.3. Impacts on Terrestrial Ecosystems from the Massive Expansion of Cropland

The massive expansion of cropland has had significant ecological impacts on terrestrial ecosystems, especially in the context of rapid urbanisation and agricultural development. According to our study, we found that the massive expansion of cropland in Cambodia, driven by population and economy, has led to the occupation of a large amount of ecological land and increased fragmentation of ecological land. At the same time, there is an imbalance in the structure of land use types in Cambodia, and ecosystems such as forests and shrubs have been severely damaged. For example, the proportion of forests in the country continues to decline, while arable land continues to rise, with the proportion of arable land (37.87%) catching up with the proportion of forests (40.19%) in 2023. This imbalance is prevalent in tropical regions across the world. For example, the Brazilian Amazon has experienced massive deforestation due to agro-pastoral development [80]. The expansion of crops in the Ghanaian region of Africa caused 78% of forest loss between 1986 and 2015 [81]. Ecosystems are at serious risk of degradation as a result of the massive expansion of cropland. For example, as the area of ecosystems, such as forests, is further reduced, the original biodiversity will suffer irreversible damage, and some species of flora and fauna may be threatened with extinction [82,83]. Extending from the specifics of the tropics to a global scale, we can see that the effects of arable land expansion are pervasive and far-reaching. The study noted a surge in the expansion of cropland in protected areas from 2000 to 2019, 58 times faster than the global rate of cropland expansion, which poses a threat to biodiversity [65]. In addition, the reduction of ecological land directly weakens carbon storage capacity, leading to more greenhouse gas emissions into the atmosphere

and exacerbating the impacts of climate change [75,84]. For example, regional warming and drying due to deforestation has resulted in an additional 5.1% loss of above-ground biomass carbon storage in the Amazon region. This increase in carbon emissions in turn further contributes to climate change [75]. Expansion of cropland may also trigger environmental problems such as soil degradation, soil erosion, and water quality deterioration [85]. These problems are universal and serious on a global scale. Thus, the impact of cropland expansion on global ecosystems is multifaceted, threatening not only biodiversity and the carbon cycle, but also posing challenges to climate change and water conservation. Global cooperation and innovative strategies are therefore needed to address these challenges.

5.4. Limitations of the Study

This study provides insights into the spatial and temporal variability of cropland encroachment on ecological land and its drivers in Cambodia, with some limitations. In the selection of land use data, the scope of the study mainly focuses on the period after 2000 and fails to cover the situation before 2000 due to the temporal resolution of the data. At the same time, since the land use data are derived from remote sensing images, there may be deviations from the actual land use situation. Future studies could use higher resolution remote sensing imagery to more accurately monitor trends in cropland expansion. In terms of the analysis of influencing factors, limited by the temporal resolution of data such as GDP, the quantitative analysis of the drivers of arable land expansion in this study is only up to 2019. Thus, it fails to fully compensate for the research limitations caused by the insufficient temporal resolution of raster data. In addition, this study considered the impact of factors such as population and precipitation on the expansion of arable land mainly at the macro level. It fails to adequately consider the role of micro-level factors such as technological progress and water availability. In terms of research methodology, Despite the advantages of the XGBoost-SHAP model, it also faces challenges such as model interpretability, under-explaining of feature interactions, complexity of parameter tuning, and uncertainty of model generalisation ability. Future research needs to integrate more data resources, apply advanced statistical techniques, improve the explanatory power and predictive accuracy of the model, and comprehensively analyse the drivers of cropland expansion.

6. Conclusions

This study reveals the spatial and temporal characteristics of ecological land encroachment by cropland expansion and its drivers in Cambodia, which provides an important basis for understanding the impact of land use change on the ecosystem. The results show that (1) the area of cropland in Cambodia showed an upward trend during the period of 23 years, with the area increasing by 26,865.08 km². The proportion of cropland (including dry land and rice fields) in the country's land area increased from 25.31% in 2000 to 38.78% in 2023, an increase of 13.47%. Agricultural land is mainly dominated by rice paddies, supplemented by drylands, with strong changes in the area of drylands, while rice fields are more stable. (2) Both drylands and rice fields show significant spatial clustering. Drylands are mainly concentrated in the mountainous areas in the east and west and the border area with Thailand in the north, while rice paddies are mainly distributed in the plains in the centre of Cambodia. (3) Drylands and rice fields mainly encroach on forests and shrubs. Cultivated land expansion significantly exacerbated the fragmentation of ecological land, and the fragmentation of ecological land around drylands and rice fields increased. (4) Single and multifactor interaction analyses showed that soil type and GDP and their interaction dominated the expansion of dryland area. Altitude and population dominated the expansion of rice fields. Whereas the interaction of elevation with population and soil type had the strongest effect on the expansion of rice fields. In addition, precipitation significantly affected the distribution and dynamics of dryland and rice paddies. The over-expansion of cropland is the most pressing issue in Cambodia today. How to balance the relationship between economic development and ecological protection to ensure that agricultural expansion meets the demand for food security while not causing excessive pres-

sure on the ecological environment. The study provides practical guidance for Cambodia to optimise the agricultural layout and promote the sustainable use of arable land resources. It also provides lessons for regions around the world that are facing the same problems.

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