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Temporal and Spatial Evolution Characteristics and Its Driving Mechanism of Land Use/Land Cover Change in Laos from 2000 to 2020

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Abstract: Land use/land cover change (LUCC) research is of great significance to land conservation and regional sustainable development. At present, there is a lack of research on the long-term timing of the change process and mechanisms of LUCC that accords with the national level in Laos. Based on the Global Land-Cover product with the Fine Classification System at 30 m (GLC_FCS30) data set as well as economic and social statistical data, the authors analyzed the spatiotemporal regularity and driving mechanism of LUCC in Laos from 2000 to 2020 by using dynamic degree, flow direction analysis, principal component analysis, correlation analysis and other methods. The results show that: (1) Laos is rich in natural ecological resources. In 2020, the forest and shrubland areas accounted for 53.3% and 32.4% of the land area, respectively; (2) from 2000 to 2020, the rate of LUCC across the country continued to rise, and the integrated dynamic degree of LUCC was 14.4%. The change in impervious surfaces is the most drastic. The area of evergreen broad-leaved forest, evergreen needle-leaved forest and grassland continued to shrink, while the area of rainfed cropland, irrigated cropland, deciduous broad-leaved forest, shrubland, wetland and the water body continued to expand; (3) the LUCC process mainly occurred between forest, shrubland and cropland. The LUC with the largest transfer out area is evergreen broad-leaved forest (8.91×10^3 km^2), and the LUC with the largest transfer into the area is shrubland (8×10^3 km^2); (4) in the past 20 years, the LUCC process in Laos has been mainly affected by macro-socioeconomic development, agricultural development, and forestry development. The population is the key factor driving LUCC in Laos. This study can provide decision-making support for the rational planning and utilization of land resources in Laos.

Keywords: land mapping; LUCC; time-series analysis; national development

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1. Introduction

The land is the most basic natural resource and the material basis for human economic and social activities. Land use/land cover (LUC) characterizes the activities of human land resource development and the physical and biological cover types on the Earth's surface. Land use/land cover change (LUCC) is the most direct characterization signal that various human production activities act on the Earth's surface ecological environment [1,2], involving many important issues such as global climate and ecological environment changes, surface energy cycles and human survival and development [3–5].

In 1990, the Global Change Committee of the National Research Council (NRC) in the United States first proposed the LUCC research framework. In 1995, the International Geosphere-Biosphere Program (IGBP) and the International Human Dimensions Programme on Global Environmental Change (IHDP) jointly proposed the "LUCC" research project, which mainly focuses on land use/land cover changes driven by human activities and global changes and their impact on the environment and society [6]. Since then, LUCC has quickly become a hot spot in global change research. In 2005, IGBP and IHDP jointly launched the Global Land Programme (GLP), which aims to understand how people interact with the environment and how different terrestrial systems interact and influence [7]. In 2014, the International Council of Scientific Unions (ICSU) and the International Social Science Council (ISSC), together with UNESCO, the United Nations Environment Programme (UNEP) and other international organizations, launched the "Future Earth" (2014–2023). The program aims to improve global sustainability, focusing on the coupling of LUCC processes, ecosystem services, and human well-being at different scales [8].

For decades, researchers from various countries have carried out a large number of studies on LUCC monitoring, LUC mapping, analysis of temporal and spatial changes, and discussion of driving mechanisms. Zhu et al. developed a CCDC (Continuous Change Detection and Classification) algorithm for continuous monitoring of multiple LUCC and provided land cover maps of 16 categories with an overall accuracy of 90% at a given time [9]. Nasiri et al. evaluated the potential of Sentinel-2 and Landsat-8 time series and random forest classifiers to produce LUC maps, proving that new Earth observation satellites such as Sentinel-2 can accurately and quickly generate LUC maps based on cloud computing GEE [10]. Using a supervised classification method, Hussain et al. explored LUC changes in the Okara region based on various Landsat images [11]. Gibbs et al. explored the changes in agricultural land in the tropics in the 1980s and 1990s and found that tropical rain forests were the main source of agricultural land expansion, and the large-scale expansion of agro-industries was the main driver of deforestation [12]. Lambin et al. also believe that the transformation of forests into farmland and pastures is a common phenomenon in LUCC in tropical regions, and this change is driven by synergistic factors of resource scarcity [13]. Lambin et al. also proposed that economic development was the driving factor of LUCC, local and national policies were the constraining factors of LUCC, and globalization was its main determinant [14]. At the same time, the advancement of LUCC research has increased the demand for LUC products on global and regional scales. For example: NASA provided MCD12Q1 products that are updated year by year (2000–2020) based on Terra and Aqua combined MODIS, with a spatial resolution of 500 m [15]; The European Space Agency (ESA) released two datasets with a resolution of 300 m, GLOBCOVER and CCI_LC [16]; China National Geographic Information Center released GlobeLand30, a global surface coverage product with a resolution of 30 m, in three versions: 2000, 2010, and 2020 [17]; The Institute of Aerospace Information Innovation, Chinese Academy of Sciences released the 1985–2020 global land cover fine classification product GLC_FCS30 (Global Land-Cover product with Fine Classification System at 30 m), with a spatial resolution of 30 m [18], etc. Various products are developing in the direction of long time series and high precision, and these products also provide stronger data support for further in-depth LUCC research.

Laos is the only landlocked country in the China-Indochina Peninsula, with an extremely undeveloped economy, and until 2021 it was listed by the United Nations as one of the 46 "least developed countries" in the world. Most of the current research on Laos was based on independent satellite remote sensing land mapping, which lacks unified and reliable primary data, and it is not easy to carry out comparative research. Moreover, most of the studies were conducted at a regional scale such as provinces, river basins, and cities, and there were few studies on the temporal and spatial LUCC at the national scale in Laos. For example, using land use maps obtained by interpreting Landsat 5 TM satellite images, Boundeth et al. discussed the LUCC and its influencing factors in four periods of 2001, 2004, 2007, and 2010 in Bokeo Province, Laos [19]. Liu et al. interpreted and classified the regional LUC by using Landsat TM (Thematic Mapping Instrument)/ETM+ (Enhanced Thematic Mapping Instrument) images in 1990, 2000, and 2010, and explored the main changing characteristics of wetlands and rubber forests in Luangnamtha Province, northern Laos [20]. Faichia et al. analyzed the historical land use in Vientiane through the images acquired by Landsat 5 TM in 1995 and 2004, and the images acquired by Landsat 8 OLI in

2013 and 2018 [21]. Inoue et al. studied the dynamic changes in land use and ecosystem carbon storage in the tropical mountainous areas of Laos. The land use information data in the study area were mainly obtained through field visits, satellite images, digital maps, and geo-referenced photos taken with GPS cameras [22]. In general, due to the lack of detailed, reliable, and long-term LUC datasets, the region has been lacking a national-scale LUCC spatiotemporal analysis study, and the exploration of the driving mechanism of LUCC is only qualitative analysis, lacking quantitative statistical reasoning and model simulations.

In response to the above problems in the Laos LUCC studies, the authors collected the long-term, high-resolution GLC_FCS30 data set, key national economic development, and social development data. Based on these data, this paper analyzed the temporal and spatial patterns and dynamic changes of LUC in Laos and discussed the impact of regional climate, population, and economic development in Laos on its LUCC process. We attempt to respond to the following three queries:

1. What are the distribution patterns and temporal changes in LUC in Laos from 2000 to 2020?
2. What are the key drivers of LUCC in Laos from 2000 to 2020?
3. What are the uncertainties that exist in the analysis of LUCC in Laos?

2. Data and Methods

2.1. Study Area

Laos, the only landlocked country in the region, is located in the northern part of the China–Indochina Peninsula (13°56′–22°27′ N, 100°02′–107°38′ E). Laos borders China to the north, Cambodia to the south, Vietnam to the east, Myanmar to the northwest, and Thailand to the southwest. There are 16 provinces, one municipality directly under the Central Government and one special administrative region, with a total land area of 23.68×10^4 km^2. The northern region, the central region, and the southern region make up the three sections of the nation. Among them, the northern region includes 7 provinces of Phongsaly, Luangnamtha, Bokeo, Oudomxay, Luangprabang, Huaphanh, and Xayaboury. The central region includes Vientiane, Xiengkhuang, Borikhamxay, Savannakhet, Khammuane, Vientiane Capital, and Xaysomboon. The southern region includes the 4 provinces of Saravan, Xekong, Champasack, and Attapeu.

Laos has a simple climate type, a tropical and subtropical monsoon climate, and the year can be divided into two seasons: the rainy season (May to October) and the dry season (November to April). The average temperature during the rainy season ranges from 25 °C to 30 °C, the average temperature in the dry season is about 15 °C, and the national annual average temperature is roughly 26 °C. Over the entire area, there is abundant rainfall. The annual precipitation ranges from roughly 1250 mm to 3750 mm, with an average of about 2000 mm.

The geography in Laos is high in the north and low in the south, as well as high in the east and low in the west. Laos is long from north to south and narrow from east to west. The largest river in Laos is the Mekong, which passes through the nation's capital Vientiane and serves as a boundary river between Laos and Thailand, Laos and Myanmar. Among them, the Xiangkhong Plateau in the northern region is the highest, with an altitude of 2000–2800 m. The plains in the territory are mainly distributed along the Mekong River south of Vientiane, and in the west are the Mekong Valley, basins, and small alluvial plains along the Mekong River and its tributaries (Figure 1).

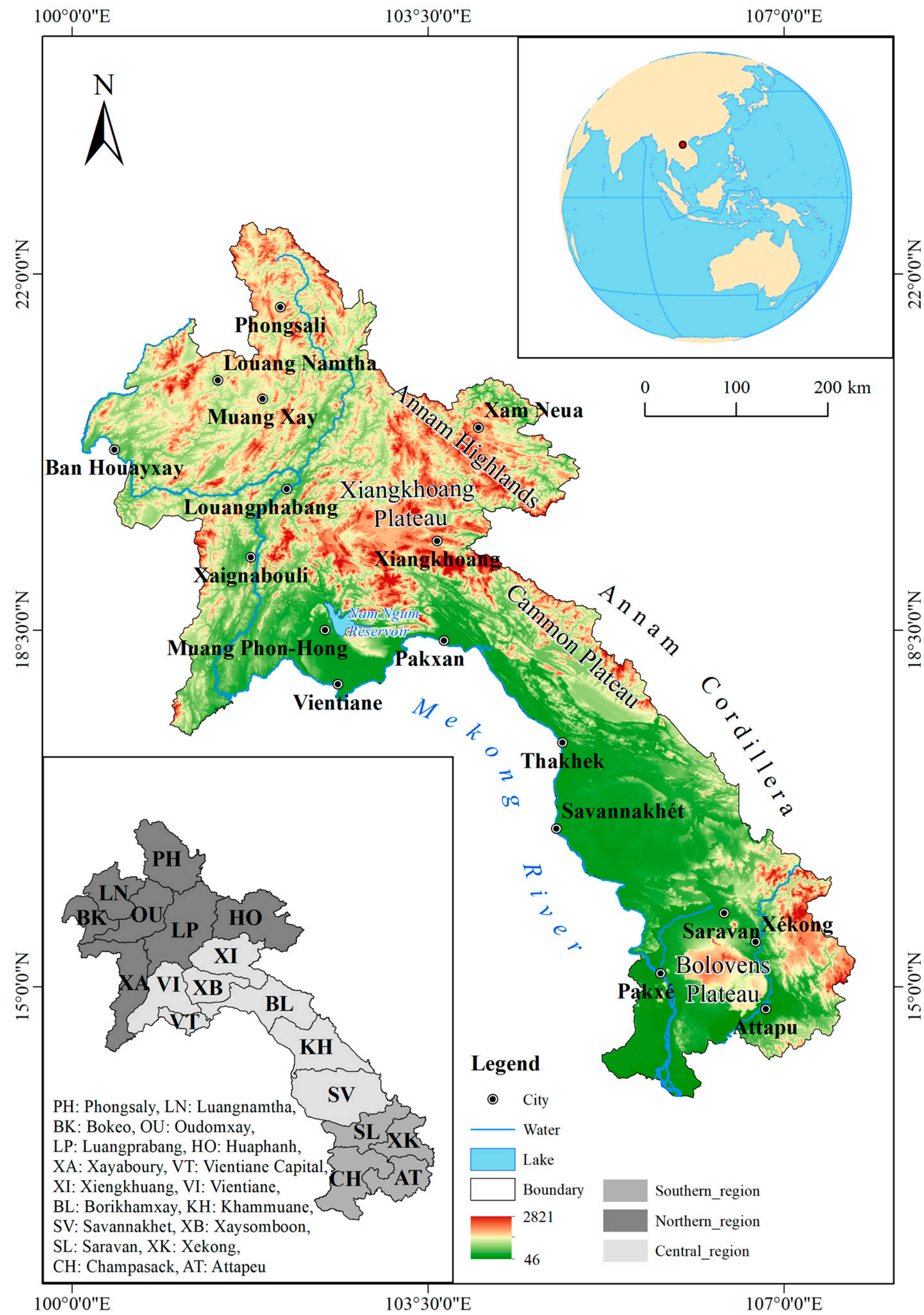


Figure 1. Location and topography map of Laos.

Laos is generally an agricultural country with an extremely underdeveloped economy. Rice is its main agricultural product, and over 60% of its cropland is used for rice cultivation, mainly along the Mekong River (e.g., Vientiane, Khammuane, Borikhamxay, Savannakhet, Saravan and, Champasack). Other agricultural products include corn, cassava, sugar cane, fruits, vegetables, etc. Laos has a large number of forest resources, and it has long exported precious wooden raw products such as mahogany and teak to China, Vietnam, and other nations. Ironwood, mahogany, pine, mahogany, and teak are the main wood varieties.

2.2. Data Sources

The long-term, high-precision LUC data set (2000–2020, a total of 5 periods) used in the research comes from the GLC_FCS30 data set of the global 30-m surface coverage fine classification product released by the research team of Liu from the Institute of Aerospace Information Innovation, Chinese Academy of Sciences [23] GLC_FCS30 includes 9 first-level

LUC types and 30 s-level fine LUC types. The complete time series covers 8 time periods from 1985 to 2020. The overall classification accuracy rate is 82.5%, and the secondary classification accuracy rate is 68.7% [24]. In Laos, there are a total of 18 s-level land types. According to the actual situation of LUC in the study area, this paper subdivided the farmland and forest into two-level land types. That is, the cropland is divided into two types: rainfed cropland and irrigated cropland, and the forest is divided into three types: evergreen broad-leaved forest, deciduous broad-leaved forest, and evergreen needle-leaved forest. Grassland and bare areas are grouped, and wetland and water body are grouped. For other land types, the analysis is carried out on the first-level LUC types (Table 1).

Table 1. LUC classification system in Laos.

Code	Level 1 Classes	LUC ID	Level 2 Classes
1	Rainfed cropland	10	Rainfed cropland
		11	Herbaceous cover
		12	Tree or shrub cover (orchard)
2	Irrigated cropland	20	Irrigated cropland
3	Evergreen broad-leaved forest	51	Open evergreen broad-leaved forest
		52	Closed evergreen broad-leaved forest
4	Deciduous broad-leaved forest	61	Open deciduous broad-leaved forest (0.15 < fc < 0.4)
		62	Closed deciduous broad-leaved forest (fc > 0.4)
5	Evergreen needle-leaved forest	71	Open evergreen needle-leaved forest (0.15 < fc < 0.4)
		72	Closed evergreen needle-leaved forest (fc > 0.4)
6	Shrubland	120	Shrubland
		121	Evergreen shrubland
7	Grassland	130	Grassland
		200	Bare areas
8	Impervious surfaces	190	Impervious surfaces
9	Wetland and water body	210	Water body
		220	Permanent ice and snow
		180	Wetland

The long-term meteorological data (2000–2020) used in the study are from the GLDAS-2.1 [25] and PERSIANN-CDR [26] datasets. The spatial resolution of the original datasets is all 0.25 radians. Based on the daily data obtained from the above datasets, the authors further calculated the total annual precipitation, rainy season precipitation, and average annual temperature in the study area. The long-term economic and social statistics (2000–2020) used in the study come from the World Bank [27], Knoema [28], and the World Food and Agriculture Organization (FAO) [29].

Based on the climate change status, national economic structure, and production of major agricultural and forestry products in Laos over the past 20 years, the authors selected 19 meteorological and economic and social statistical indicators as shown in Table 2, and tried to select the driving factors that drive LUCC in Laos.

Table 2. Indicators and their categories of economic and social development statistics.

Category	Index	Unit
Climate	X1 Average annual temperature	°C
	X2 Total annual precipitation	mm
	X3 Rainy season precipitation	mm
Social development	X4 Gross population	10,000 people
	X5 Rural population	10,000 people
	X6 Urban population	10,000 people
	X7 Urbanization rate	%

Table 2. *Cont.*

Category	Index	Unit
Economic development	X8 Gross Domestic Product (GDP) X9 Agricultural value added X10 Industrial value added X11 Hydroelectricity Net Generation	100 million (current USD) 100 million (current USD) 100 million (current USD) Billion Kilowatthours
Production	X12 Rice X13 Maize X14 Cassava X15 Sugar cane X16 Fruit X17 Vegetables X18 Roundwood X19 Sawnwood	t t t t t t m^3 m^3

Note: X1–X3 are from the GLDAS-2.1 and PERSIANN-CDR datasets; X4–X10 are from the World Bank: X11–X19 are from the Knoema and the World Food and Agriculture Organization.

2.3. LUCC Analysis Method

The land-use dynamic degree quantitatively describes the change rate of land use and can be divided into integrated land-use dynamic degree and single land-use dynamic degree [30].

The integrated land-use dynamic degree is used to describe the overall change degree of land use in the study area during a certain study period. This value is proportional to the dynamic change in LUC types within a certain period time in the region. The larger the integrated dynamic value, the stronger the dynamic change in LUC types, and vice versa. The expression [31] is as follows:

$$D = \left\{ \sum_{i=1}^{n} \left(\frac{\Delta S_i}{S_i} \right) \right\} \times \frac{1}{T} \times 100\% \quad (1)$$

where D is the integrated land-use dynamic degree during the study period time; n is the number of land use types; S_i is the total area of the i-type LUC at the beginning of the study; ΔS_i is the sum of the area of the i-type LUC converted to other types of LUC during the period from the beginning of the study to the end of the study; T is the research period.

The single land-use dynamic degree is used to describe the transformation of certain LUC into other LUC in a certain study period in the study area. The single dynamic value is proportional to the dynamic change in a certain LUC within a certain period time in the area. The expression [31] is as follows:

$$D_i = \frac{\Delta S_i}{S_i} \times \frac{1}{T} \times 100\% \quad (2)$$

where D_i is the dynamic degree of the i-type LUC during the study period.

The land transfer matrix is in the form of a two-dimensional matrix to describe the transfer in and out of different types of LUC in the study area at the beginning and end of the study. It can not only reflect the static data of the LUC area at a fixed time, but also represent the dynamic change in the LUC during the study period [32]. The expression [33] is as follows:

$$S_{ij} = \begin{bmatrix} S_{11} & S_{12} & \cdots & S_{1n} \\ S_{21} & S_{22} & \cdots & S_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ S_{n1} & S_{n2} & \cdots & S_{nn} \end{bmatrix} \quad (3)$$

where S represents the land area; i and j represent the LUC types at the beginning and end of the study period, respectively; n represents the number of LUC types.

2.4. Analysis of Driving Mechanism

Principal component analysis (PCA) uses mathematical transformation and dimensionality reduction ideas to convert multiple correlation indicators into several irrelevant comprehensive indicators under the premise of the least loss of data information in order to remove duplicate information and eliminate data redundancy. The generated comprehensive index is the principal component, and the comprehensive index with a larger variance is selected to replace the original variable. If one principal component is not enough to represent the original variable, you need to look for the second, third..., the covariance of the selected principal component is zero, and its direction is geometrically shown to be orthogonal. The selection method is as follows:

$$\begin{cases} Y_1 = c_{11}Z_1 + c_{12}Z_2 + \cdots + c_{1n}Z_n \\ Y_2 = c_{21}Z_1 + c_{22}Z_2 + \cdots + c_{2n}Z_n \\ \vdots \\ Y_n = c_{n1}Z_1 + c_{n2}Z_2 + \cdots + c_{nn}Z_n \end{cases} \tag{4}$$

Among them, Y_i represents the i principal component, $i = 1, 2, \ldots, n$; c is the eigenvector corresponding to the eigenvalues of the covariance matrix; Z is the normalized value of the original variable; where $c_{i1}^2 + c_{i2}^2 + \cdots + c_{in}^2 = 1$ for each i.

LUCC is affected by various factors such as nature, humanities, and social economy. Multiple linear stepwise regression uses the optimal combination of multiple independent variables to more effectively predict or estimate dependent variables. In this study, each LUC type is an independent variable, and indicators such as climate, population, and economic and social development are dependent variables, and a multiple linear stepwise regression analysis is carried out. The multiple regression model is as follows:

$$Y = \beta + \alpha_1\ X_1 + \alpha_2\ X_2 + \ldots + \alpha_n X_n \tag{5}$$

where, $\alpha_1, \alpha_2, \ldots, \alpha_n$ represent the correlation coefficient; β is a constant term.

3. Results

3.1. Spatial Distribution

Laos is rich in natural ecological resources. In 2020, the proportion of natural vegetation coverage such as forest and shrubland was extremely high, accounting for 85.7%. Forest (total area: 12.61×10^4 km^2, percentage: 53.3%) was the most widely distributed, more than half of the country's land area, mainly existing in the form of evergreen broad-leaved forest (8.34×10^4 km^2, 35.2%), followed by deciduous broad-leaved forest (2.59×10^4 km^2, 11%) and evergreen needle-leaved forest (1.68×10^4 km^2, 7.1%). Shrubland (7.67×10^4 km^2, 32.4%) was the second-largest LUC type in the territory. Cropland (3.01×10^4 km^2, 12.7%) was the third-largest LUC type in the country, mainly rainfed cropland (2.85×10^4 km^2, 12%), and a few irrigated cropland (0.16×10^4 km^2, 0.7%). The total area of wetland and water body, impervious surfaces and grassland accounts for only 1.6% of the national land area, including wetland and water body (0.27×10^4 km^2, 1.2%), impervious surfaces (0.09×10^4 km^2, 0.4%), and grassland (0.02×10^4 km^2, 0.1%).

From a spatial perspective (Figure 2), the evergreen needle-leaved forest was mainly distributed in high-altitude areas within the territory. The largest forest type in Laos was evergreen broad-leaved forest, which was widely distributed in middle-altitude and high-altitude areas. The deciduous broad-leaved forest was mainly distributed in low-altitude hills and plains. Shrubland was also widely distributed, concentrated in the middle-altitude areas of the country. Rainfed cropland was concentrated in the central region, such as Vientiane and the plains along the Mekong River south of Vientiane, and several small basins along the Mekong River and its tributaries to the north of Vientiane. Irrigated cropland had only a small distribution around rivers and lakes. Wetlands and water body were mainly distributed in the Mekong River region. In addition, there were also some artificial water bodies, such as the Nakai Reservoir in Khammuane, and the remaining reservoirs in the Nam Ngum River. The distribution of impervious surfaces was small and rarely scattered, covering the entire study area, which was relatively concentrated in Vientiane, the capital. The grassland area was small and distributed, mainly in the Gammon Plateau.

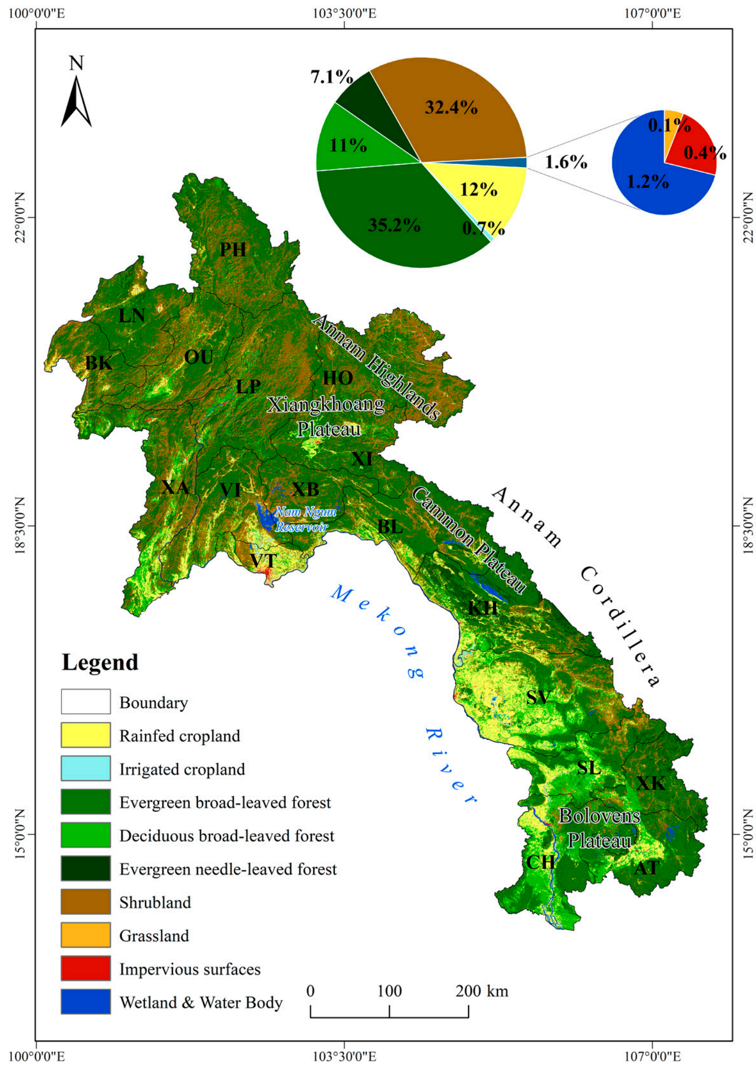


Figure 2. LUC map of Laos in 2020.

3.2. Spatio-Temporal Dynamic Changes

From 2000 to 2020, evergreen broad-leaved forest (change area: -7.6×10^3 km^2, change rate: -8.3%), evergreen needle-leaved forest (-70.85 km^2, -0.4%), and grassland (-108.30 km^2, -32.4%), showed an overall downward trend, while the rest of the land area has increased to varying degrees. Of these, the impervious surface was the LUC type with the most drastic changes in the territory (+583.62 km^2, +196.7%), and the shrubland was the LUC type with the largest area increase in the territory (+3.8×10^3 km^2, +5.2%). Judging from the changing trend of LUCC dynamic degree, the integrated land-use dynamic degree (D) generally showed an increasing trend; after 2015, however, the integrated land-use dynamic degree decreased slightly. The dynamic degree of the impervious surface was consistently much higher than that of other LUC during the study period. The dynamic degree of rainfed cropland, irrigated cropland, evergreen broad-leaved forest and deciduous broad-leaved forest had similar trends, with a slight decrease from 2010 to 2015, but an overall increase. Although the area of evergreen needle-leaved forest has decreased in general, the reduction in its area has been slowing down, and the dynamic has become positive after 2015. The overall change in shrubland dynamic was relatively stable. The dynamic degree of grassland and wetland and water body peaked in 2005–2010 and 2010–2015, respectively, and then gradually decreased (Figure 3).

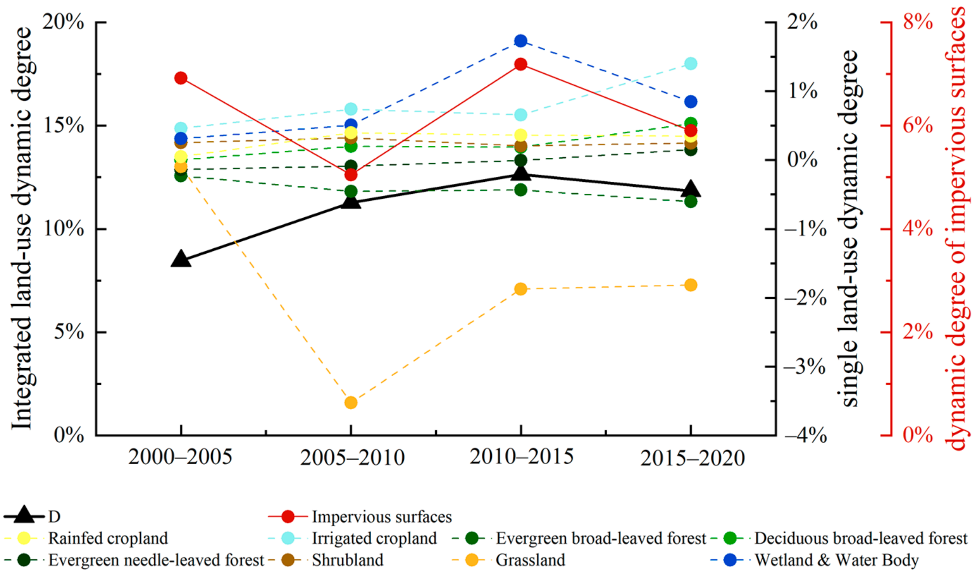


Figure 3. Dynamic degree of LUCC in Laos from 2000 to 2020.

From a spatial perspective (Figure 4), the land change dynamics in the northern and southern ends of Laos were high, while the land change dynamic in the central region was relatively low. From 2000 to 2005, the integrated land-use dynamic degrees in most provinces were below 15%, the lowest was 6.3% (Borikhamxay), and the highest was 20.7% (Oudomxay). The high-intensity LUCC in Oudomxay in the north was mainly due to the extensive expansion of the impervious surface (+80.4%) in Muang Xay, the capital of the province. From 2005 to 2010, the activity of LUCC in northern and southern Laos decreased, and the integrated land-use dynamic degrees in most provinces were below 10%. Compared with the previous period, the lowest (6.9%, Savannakhet) and highest (35.1%, Xaysomboon) integrated land use dynamic degrees have increased. Data showed that the changing intensity of impervious surface was the main factor affecting the land use dynamics. From 2010 to 2015, the intensity of LUCC in all provinces showed an upward trend. During this period, the integrated land-use dynamic degrees in most provinces exceed 10%, the lowest was 7.2% (Champasack), and the highest was 249.9% (Xaysomboon). The main reason for the drastic LUCC in Xaysomboon was the large expansion of grassland (+1054.4%). In addition, there were also large-scale increases in impervious surface (+124.8%), wetland and water body (+51.5%) in the province. From 2015 to 2020, the intensity of LUCC in the northern and southern regions increased, and the land use activity in the central region decreased. Most provinces' integrated land-use dynamic degree exceeded 15%, with the lowest being 7.9% (Vientiane Capital) and the highest being 50.2% (Attapeu). The increased LUCC in the south of Attapeu was mainly due to the rapid growth of wetland & water body (+101.4%).

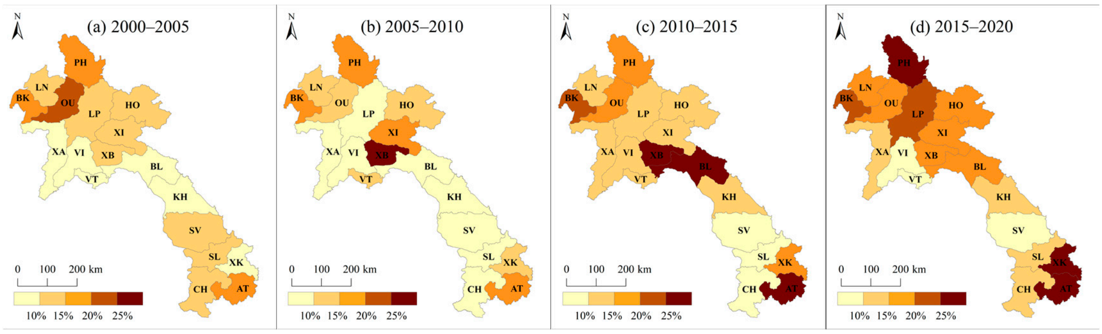


Figure 4. The spatial distribution map of integrated dynamic degree of LUCC in Laos.

3.3. Source and Destination

The land area of LUC transfer (in or out) in Laos was about 9.69 × 10^3 km^2 from 2000 to 2010, and the land area transfer from 2010 to 2020 was about 11.5 × 10^3 km^2. The change process of LUC was mainly reflected in the one-way conversion of forest to shrubland and forest to cropland (Figure 5).

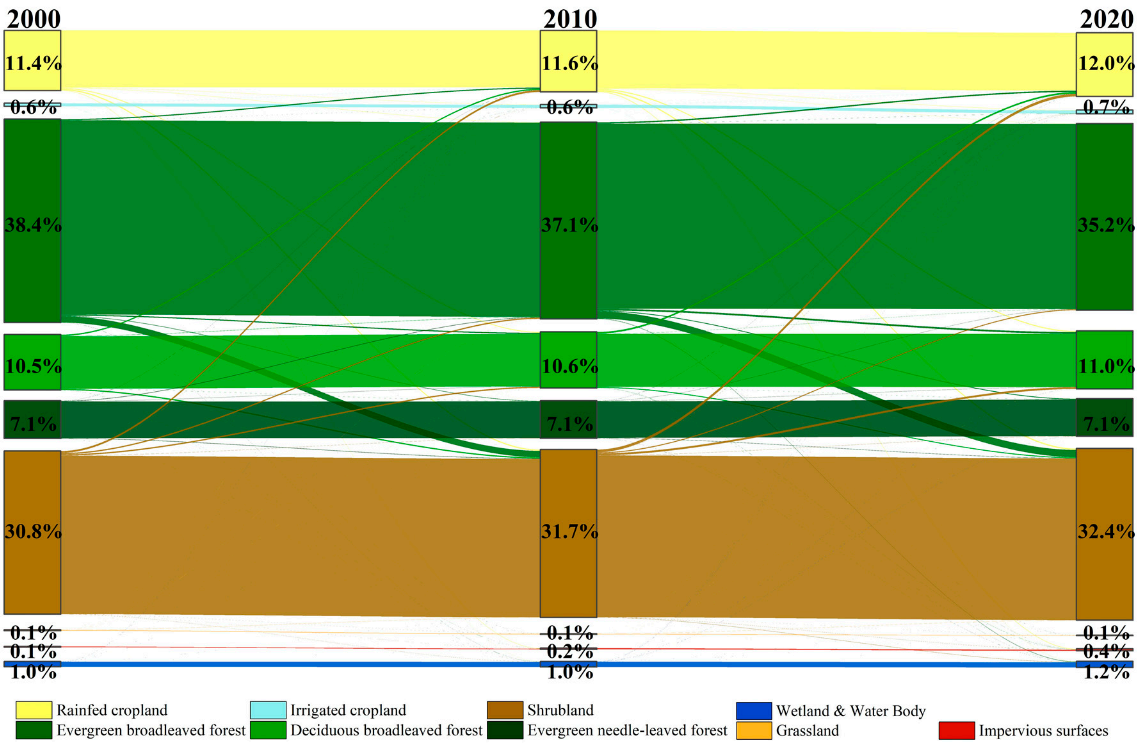


Figure 5. LUC transfer plot of Laos during 2000–2020.

The area of cropland showed a trend of continuous expansion. Rainfed cropland was the main body of Laotian cropland. From 2000 to 2020, the area of lost rainfed cropland was about 2.71 × 10^3 km^2, which was mainly converted to deciduous broad-leaved forest (28.2%), shrubland (36.8%), and impervious surface (14.8%). Moreover, rainfed cropland grew by 4.29 × 10^3 km^2, and about 96% came from evergreen broad-leaved forest, deciduous broad-leaved forest, and shrubland. The loss of rainfed cropland mainly occurred in the four provinces of Luangprabang, Huaphanh, Xiengkhuang, and Champasack. Except for the above-mentioned four provinces, the rainfed cropland area of other provinces has increased, and the province with the most obvious expansion was Borikhamxay (+21.5%) (Figure 6a). The area of irrigated cropland has also shown an expanding trend over the past 20 years. In total, about 146.2 km^2 of irrigated cropland area was lost, which was mainly converted to rainfed cropland (43.9%), wetland and water body (24.9%), and impervious surface (18.1%). The area of irrigated cropland obtained from other LUC was approximately 389.2 km^2, of which about 60% came from rainfed cropland. The decrease in the area of irrigated cropland was mainly concentrated in the northern region (Luangprabang, Oudomxay, Xayaboury) and the central region (Vientiane Capital). In addition, the rest of the provinces showed an expansion trend, and the province with the most obvious expansion was Saravan (+69.9%) (Figure 6a). The expansion of irrigated cropland reflected the gradual improvement of agricultural water conservancy facilities in Laos, which was also conducive to the stabilization of the country's agricultural development.

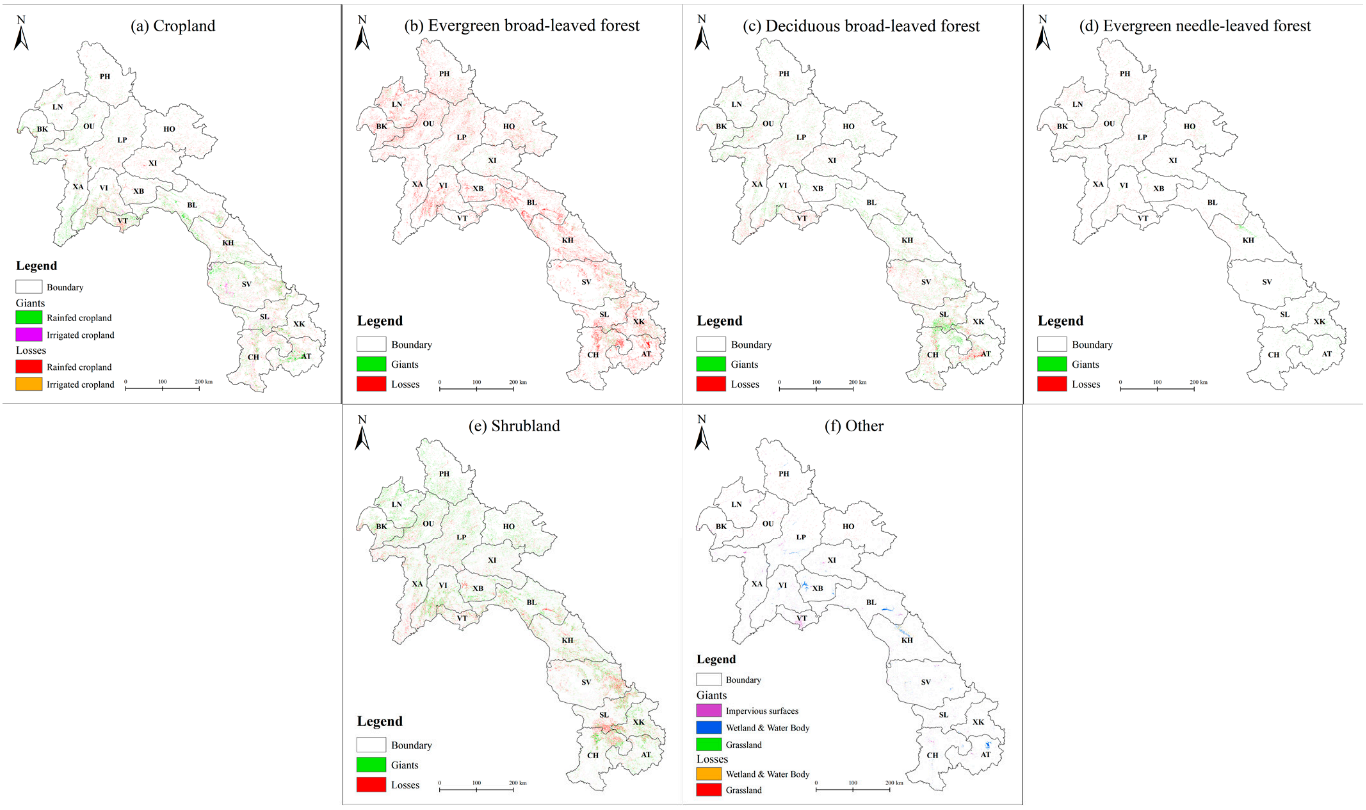


Figure 6. Spatial distributions of different LUC types gains/losses during 2000–2020.

Evergreen broad-leaved forest is the land type with the widest coverage in Laos and the largest transferred area. The total lost area of evergreen broad-leaved forest was 8.91×10^3 km^2, nearly 65% of which was converted into shrubland, nearly 27% was converted into rainfed cropland and deciduous broad-leaved forest, and a few were converted into evergreen needle-leaved forest and wetlands and water body. Meanwhile, evergreen broad-leaved forest gained an area of 1.32×10^3 km^2, of which about 57% came from shrubland, and about 40% came from rainfed cropland, deciduous broad-leaved forest, and evergreen needle-leaved forest. Evergreen broad-leaved forest is the land type with the most severe area reduction in the territory. The lost area of evergreen broad-leaved forest of all provinces was larger than the gained area. The country showed a trend of sharp reduction in evergreen broad-leaved forest, with the largest reduction in the municipality of Vientiane (−29.4%) (Figure 6b).

The lost area of deciduous broad-leaved forest was 2.38×10^3 km^2, 51% of which was converted to rainfed cropland, 35% to shrubland, and a few were converted to other LUC types. The deciduous broad-leaved forest gained area of 3.53×10^3 km^2, and nearly 95% came from the evergreen broad-leaved forest, shrubland, and rainfed cropland. The deciduous broad-leaved forest showed an overall expansion trend, with the most obvious expansion in Borikhamxay (+21%). Within the territory, only Attapeu (−5.4%) and

Vientiane Capital (−12.6%) saw a reduction in the area of deciduous broad-leaved forests (Figure 6c).

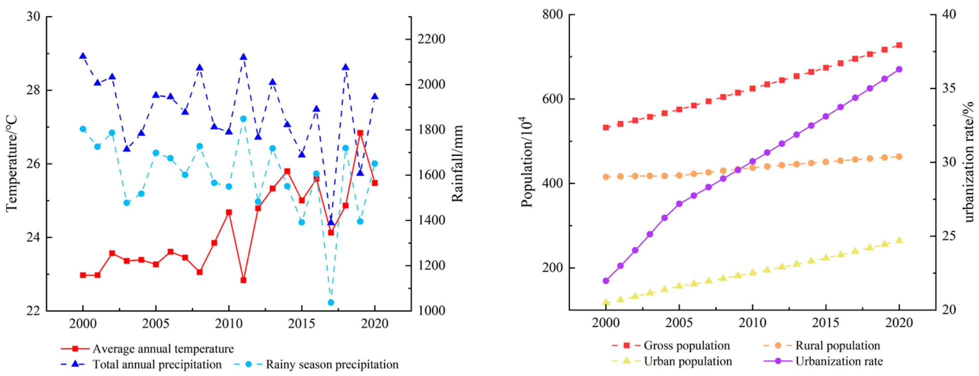
The lost area of evergreen needle-leaved forest was about 780 km^2, mainly converted to two kinds of broad-leaved forest and shrubland. Evergreen needle-leaved forest increased by a total of 709 km^2, 72% of which came from evergreen broad-leaved forest. In addition, the area growth of evergreen needle-leaved forest was concentrated in the four provinces of Vientiane Capital, Xaysomboon, Khammuane, and Savannakhet in the central region, as well as all the provinces in the southern region. The area loss of evergreen needle-leaved forest mainly occurred in the four provinces of Vientiane, Xiengkhuang, Huaphanh, and Borikhamxay, as well as all provinces in the northern region (Figure 6d).

Shrubland is the second-largest land type in the territory, and it is also the land type with the largest area increase. The area of Shrubland increased by 8×10^3 km^2, with 72% coming from evergreen broad-leaved forest and some from rainfed cropland and deciduous broad-leaved forest. The area of Shrubland lost about 4.2×10^3 km^2, and more than 90% was converted to rainfed cropland, deciduous broad-leaved forest, and evergreen broad-leaved forest, and very few were converted to other LUC types. Except for Vientiane Capital (−1.9%) and Saravan (−4.4%), the area of shrubland showed a shrinking trend, while the area of shrubland in other provinces expanded to varying degrees. The province with the most obvious expansion was Attapeu (+19.4%) (Figure 6e). The changes in Laos' shrubland land actually reflect the process of deforestation.

As for other LUC types: the impervious surface area of each province increased to varying degrees, with a total of 583.62 km^2, most of which came from rainfed cropland. The most dramatic expansion of impervious surface has occurred in Xaysomboon (+1324%) and the largest in Vientiane Capital. From 2000 to 2020, the national impervious surface increased by 583.62 km^2, and the impervious surface area of Vientiane Capital increased by 101.85 km^2. The grassland area was small and shrinking, the area loss mainly occurred in the central and southern regions, and the area increase was concentrated in the northern region. The area of wetland and water body showed an expansion trend in all provinces, and the province with the largest increase was Attapeu (+104.2%) (Figure 6f).

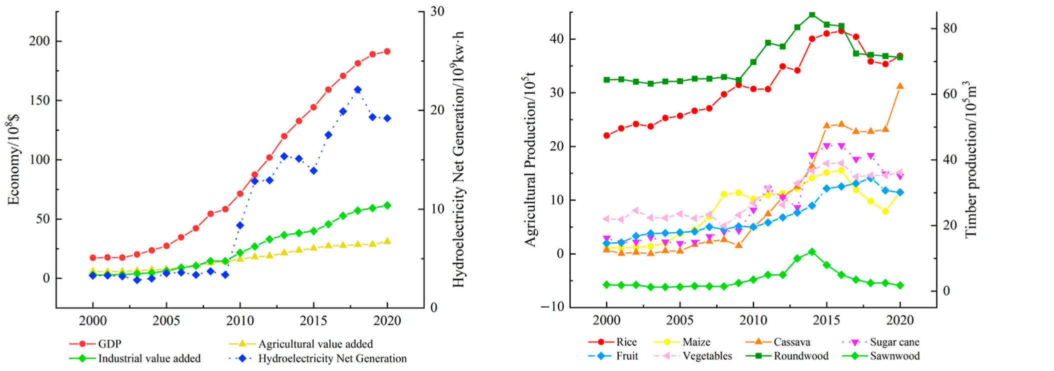
3.4. Economic, Social, Production and Climate Change Impacts

Laos showed a slight trend of becoming warm and dry as a whole from 2000 to 2020. The average annual temperature showed an overall increasing trend (+1.5 °C/10a), especially after 2010. Additionally, the annual total precipitation and the rainy season precipitation showed a slight downward trend in synchronization (annual total precipitation: −110 mm/10a, rainy season precipitation: −120 mm/10a) (Figure 7a).



(**a**) (**b**)

Figure 7. *Cont.*



(**c**) (**d**)

Figure 7. Development status of Laos from 2000 to 2020. (**a**) Climatic factors; (**b**) Population factors; (**c**) Economic factors; (**d**) Production factors.

The total population increased from 5.3 million in 2000 to 7.3 million in 2020, with a total increase of 2 million and an annual population growth rate of 1.57%. Among them, the rural population increased by about 481,500 people, with an annual growth rate of 0.55%; the urban population increased by about 1,470,300 people, with an annual growth rate of 4.15%. The level of urbanization has increased significantly, from 21.98% in 2000 to 36.29% in 2020 (Figure 7b).

From 2000 to 2020, Laos' economy developed rapidly, and the secondary industry developed rapidly. The national GDP has increased from USD 1.731 billion in 2000 to USD 19.133 billion in 2020, with a growth rate of 12.76%. The primary industry and the secondary industry maintained steady growth in synchronization with the national economy, but the growth rate of the secondary industry was much higher than that of the primary industry (16.6% vs. 8.72%). In 2008, the added value of the secondary industry exceeded the added value of the primary industry for the first time. Laos achieved a preliminary transformation from an agricultural country to an industrial country. Hydropower is an important resource in Laos. In the past 20 years, especially after 2009, the power generation of Laos' hydropower grid has grown rapidly (Figure 7c).

From 2000 to 2020, the output of major agricultural products in Laos increased steadily. Rice, corn, cassava, sugar cane, fruits and vegetables were 9.41×10^4 t/a, 6.48×10^4 t/a, 15.84×10^4 t/a, 9.9×10^4 t/a, 5.96×10^4 t/a and 5.71×10^4 t/a, respectively, continued growth. In terms of forestry, the output of roundwood and sawnwood is on the rise as a whole, with an average annual growth rate of 7.86×10^4 m^3/a and 2.04×10^4 m^3/a, respectively, over the past 20 years. The growth was rapid, especially from 2010 to 2014, however, there was a significant decline process after 2014 (Figure 7d).

From the rotated component matrix of the principal component analysis (Table 3), it can be concluded that the first principal component F1 has a strong correlation ($\geq$0.95) with 11 variables, namely: X1 average annual temperature, X4 total population, X5 rural population, X6 urban population, X8 GDP, X9 agricultural value added, X12 rice, X13 maize, X15 Sugar cane, X16 Fruit, and X17 Vegetables. Therefore, F1 is a macro-socio-economic and agricultural development factor. The second principal component, F2, is the forestry development factor because it has a strong correlation with X19 sawnwood production. Finally, the third principal component F3 has a strong correlation with the X2 total annual precipitation, which belongs to the climate change factor. Comparing the change contribution rates of F1, F2, and F3 (84.22% vs. 12.30% vs. 2.86%), the results show that: In the past 20 years, Laos' national development and changes have been mainly reflected in the field of economic and social development, especially the rapid development of the two major industries of agriculture and forestry. Compared with the impact of rapid economic and social development, the impact of climate change is not large.

Table 3. Rotated component matrix of the principal component analysis.

Variables	Description	Component		
		F1	F2	F3
X1	Average annual temperature	0.957	0.117	−0.197
X2	Total annual precipitation	−0.705	0.616	0.349
X3	Rainy season precipitation	−0.767	0.619	0.167
X4	Gross population	0.959	0.256	−0.118
X5	Rural population	0.968	0.233	−0.034
X6	Urban population	0.951	0.263	−0.148
X7	Urbanization rate	0.945	0.199	−0.234
X8	Gross Domestic Product (GDP)	0.959	0.272	0.075
X9	Agricultural value added	0.976	0.213	0.012
X10	Industrial value added	0.935	0.351	0.028
X11	Hydroelectricity Net Generation	0.945	0.314	0.058
X12	Rice	0.986	−0.154	0.016
X13	Maize	0.958	−0.244	−0.135
X14	Cassava	0.936	0.271	0.222
X15	Sugar cane	0.956	−0.199	0.208
X16	Fruit	0.977	0.023	0.137
X17	Vegetables	0.979	−0.053	0.178
X18	Roundwood	0.869	−0.457	0.187
X19	Sawnwood	0.599	−0.763	0.236
Variance		84.22%	12.30%	2.86%
Eigenvalues		16	2.34	0.54

Considering the most important LUC types in Laos (cropland, forest, shrubland, impervious surfaces), the authors used various LUC areas as dependent variables, principal components F1, F2, and F3 as independent variables, and applied multiple linear regression. The results are as follows (Table 4): The area of rainfed cropland and irrigated cropland is positively correlated with F1 and F2. This shows that during 2000–2020, with the upward economic and social development of Laos, the country's demand for food has continued to increase, which has led to the expansion of the country's farmland mainly at the expense of deforestation and reclamation. Forest area is significantly negatively correlated with both F1 and F2, and positively correlated with F3. This indicates that the country's macroeconomic society, agricultural development, and forestry development oriented towards timber exports will all lead to a reduction in forest area. The area of shrubland and impervious surface is significantly positively correlated with F1 and F2, and negatively correlated with F3. Considering that the main source of inflow of shrubland is forest, and the main source of inflow of impervious surface is rainfed cropland, this shows that population growth, economic development, and forestry development are the basic reasons for the increase in shrubland (due to deforestation) and urban development.

Table 4. Relationships between major LUC types areas and principal components in different types.

Classes	Formula	R^2
Rainfed cropland	$Y1 = 27566.93 *** + 161.71 \times F1 + 124.86 \times F2 + 12.81 \times F3$	0.98
Irrigated cropland	$Y2 = 1510.4 *** + 21.54 \times F1 ** + 26.57 \times F2 * - 7.7 \times F3$	1.00
Forest	$Y3 = 129551.03 *** - 632.3 \times F1 ** - 440.37 \times F2 * + 336.43 \times F3$	1.00
Shrubland	$Y4 = 74853.46 *** + 363.87 \times F1 ** + 207.56 \times F2 * - 369.07 \times F3 *$	1.00
Impervious surfaces	$Y5 = 551.22 * + 54.37 \times F1 * + 52.21 \times F2 - 8.43 \times F3$	0.99

Note: the significance test symbol * is $p < 0.05$, ** is $p < 0.01$, and *** is $p < 0.001$.

Considering the most important LUC types in Laos (cropland, forest, shrubland, impervious surfaces), the authors used four types of land area as dependent variables and 13 key driving factors as independent variables to perform stepwise linear regression analysis, with the following results (Table 5): Rainfed cropland is significantly positively correlated with rural population (X5), and irrigated cropland is significantly positively correlated with total population (X4) and total annual rainfall (X2). This suggests that the demand for rations caused by population growth will directly drive farmland expansion. Forest area is significantly negatively correlated with total population (X4) and rural population (X5). This indicates that the rapid growth of the total population, especially the rural population, is the main driving force behind the rapid depletion of mountain forest resources. There is a significant positive correlation between shrubland and total population (X4), which is a reflection of the subsequent increase in shrubland after large-scale deforestation due to increased population pressure. There is a significant positive correlation between impervious surface and total population (X4), suggesting that population increase is the driving factor for urban expansion.

Table 5. Relationships between major LUC types areas and driving factors.

Classes	Formula	R^2
Rainfed cropland	$Y1 = 13249.64 *** + 32.75 \times X5 ***$	0.99
Irrigated cropland	$Y2 = 406.62 *** + 1.37 \times X4 *** + 0.13 \times X2 **$	1.00
Forest	$Y3 = 160709.86 *** - 24.34 \times X3 ** - 36.38 \times X4 *$	1.00
Shrubland	$Y4 = 62639.28 *** + 19.49 \times X4 ***$	0.99
Impervious surfaces	$Y5 = -1310.51 ** + 2.97 \times X4 ***$	0.98

Note: the significance test symbol * is $p < 0.05$, ** is $p < 0.01$, and *** is $p < 0.001$.

4. Discussion

4.1. LUCC and Its Impacts and Recommendations

With economic growth, social development, accelerated urbanization, and industrial transformation, developing countries generally experience a trend of decreasing natural ecological land and increasing impervious surface [34,35]. This study shows that the area of evergreen broad-leaved forest and evergreen needle-leaved forest in Laos decreased as a whole from 2000 to 2020, while the area of other LUC types increased to varying degrees, among which the area of impervious surface increased most sharply. The above results are the same as the LUCC situation in general developing countries around the world and are also consistent with the regional-scale research results of Faichia et al. [21] and Hue et al. [36]. Their research shows that the forest land in the Vientiane region of Laos has been rapidly degraded, and the cultivated land has continued to increase due to the impact of human activities.

For Laos, where most of the land is covered by forest, the forest is not only the key to economic development, but also the material basis for its good ecological services [37]. This paper points out that from 2000 to 2020, the net transfer out value of Laos' land area is mainly represented by the transfer out of evergreen broad-leaved forest (7.59×10^3 km^2), evergreen needle-leaved forest (70.85 km^2), and grassland (108.3 km^2). The huge loss of forest ecosystem area will lead to the deterioration of ecosystem structure and the weakening of ecosystem services, threatening the biodiversity and ecologically sustainable development of Laos, and affecting the stability of regional ecosystems and the sustainability of national economic and social development. The Laos government issued an order in 2016 to ban the export of all types of unfinished wood products [38]; this has played an important role in curbing the rapid growth of deforestation and shrinking forest area in Laos since 2000. However, after 2016, the shrinking rate of forest resource area in Laos remained at a high level. How to balance the relationship between the export of forest resources and the protection of those forest resources? How to gradually improve the processing level of forest products as well as change the forestry industry structure characterized by the export of primary raw materials such as roundwood and sawnwood? These are major issues that require urgent attention from scientific researchers and the Laos government.

4.2. Driving Mechanisms and Future Research Priorities

The analysis of the driving mechanism of LUCC has always been the focus of land scientists. Curtis et al. [39], Song et al. X.P. [40], and Prabhakar [41] have all emphasized the need to attach great importance to research on this topic in their papers published in journals such as *Science*, *Nature*, and *Land Use Policy*. They pointed out that the analysis of the driving mechanism of LUCC is a key link for LUCC research to understand change, service planning, service ecological protection, and sustainable development. However, for a national LUCC that includes natural and human processes on the land surface, a direct and clear causal relationship analysis is almost impossible to achieve due to its large and complex system. Scientists mostly use correlation analysis to discuss the impact factors of LUCC. Research on the driving mechanism of LUCC at the global scale [40] shows that 60% of LUCC can be attributed to human economic and social development activities, and 40% of LUCC is related to climate change. The results of this study also show that the LUCC process in Laos in the past 20 years was mainly affected by economic and social development, agricultural development, and forestry development, while the impact of climate change was less.

Although researchers have a basic understanding of the factors that affect LUCC (such as climate change, agricultural population growth, urban population growth, economic development, and industrial activity, etc.), the key factors driving LUCC are not the same in different regions. Our research goal is to find out the factors that affect LUCC in a specific area, and to determine the specific contribution of these factors to LUCC–that is, the driving mechanism. Moreover, we are also committed to scientifically revealing and quantitatively expressing qualitative descriptions with real data. At the same time, with the further development of technology, the development and application of LUCC-driven models are also moving from traditional and classic statistical correlation analysis methods, system dynamics simulation methods, etc. to interpretable geographic artificial intelligence methods (XGeoAI).

In addition, studies have shown that commercial agriculture for international markets is the main driver of deforestation in the Amazon [42]. The authors' research in Laos also proves that timber exports to international markets are an important factor in the reduction in forest area in the region [43]. Laos and Vietnam have formed extremely close political and economic ties in the historical period, and since Laos joined the WTO in 2013, the domestic economy of Laos has gradually integrated with the world economy. The demand for agricultural products and forest products in other economies around the world will have a significant impact on the pattern of domestic land use in Laos. In addition, the opening of the China–Laos railway in 2021, the world's second-largest economy in China will have a significant impact on the domestic economy of Laos and the pattern and process of LUCC. At the same time, taking into account the future development policy orientation of Laos–especially the economic ties between Laos and China, Vietnam, and other Indo-China Peninsula countries–it may be one of the important directions for future LUCC research in Laos to carry out LUCC analysis of border lines and buffer zones between Laos and related countries.

4.3. Uncertainty of the Study

According to the verification provided by the authors of GLC_FCS30, the overall accuracy of this dataset is 82.5%, of which 94% for forest, 88% for cropland, 56.8% for shrubland, 67.3% for grassland, 79.3% for impervious surface, and 83.8% for water body [18]. Since about 80% of Laos is a mountainous plateau, the tropical and subtropical cloudy and rainy climatic conditions across the country are complex and changeable, which will increase the uncertainty of remote sensing land classification and mapping [44]. In addition, due to differences in the classification system, production methods, and spatial resolution of land cover data products, researchers using different land cover data products to conduct research on the same area may have different results [45]. The inconsistency of multi-source and multi-scale LUC data products is especially reflected in the accurate definition of the secondary forest, shrubland, grassland, and other land types.

For the selection of drivers, although in most studies the drivers are broadly classified into two categories: socio-economic factors and natural factors, they are broad in scope and complex in relationship, and a small number of factors are not sufficient to fully represent them, so the analysis results have certain limitations. This study provides an analytical approach that first uses principal component analysis to extract key drivers and then uses multiple linear stepwise regression methods to build association models. The advantage of this technical route is that it is theoretically and operationally simple and widely applied; while the disadvantage is that the driving relationships between the factors are complex, and it is difficult to express the non-linear and complex relationships using linear regression. Moreover, the current driving mechanism analysis is based on macroscopic scale and is carried out on a national scale. The current analysis ignores the spatial characteristics of the driving factors and LUCC and also fails to reveal the contribution of different factors to the LUCC process in different administrative regions and different spatial grids. In the future, it is necessary to develop a spatialised and non-linear framework for the analysis of driving mechanisms at the provincial and regional scales, or even at the grid point scale, to reveal the complex relationships between LUCC and the natural, economic and social development factors in different regions and at different pixel points, and to determine the contribution of different factors to LUCC.

5. Conclusions

Using the global public GLC_FCS30 dataset and the economic and social statistical data provided by the United Nations FAO, this paper analyzed the temporal and spatial patterns of LUCC in Laos from 2000 to 2020 and analyzed the impact of economic and social development on LUCC. At the same time, the paper also discussed the potential impact of LUCC on the sustainable development of the country and the uncertainty in the research. This research is the latest and longest time-series analysis of LUCC laws and mechanisms at the Laos national scale.

Our research points out that the LUC types in Laos are dominated by forest (12.61×10^4 km^2, 53.3%), shrubland (7.67×10^4 km^2, 32.4%), and cropland (3×10^4 km^2, 12.7%). During the period 2000–2020, Laos' forest area experienced a large shrinkage and its impervious surface showed a rapid expansion trend. The LUCC in Laos is mainly affected by socioeconomic factors, especially demographic factors, and has a low correlation with changes in natural factors. The current trend of LUCC in Laos is deteriorating the ecosystem structure, weakening the ecosystem service function, and threatening the sustainable development of the country. It is urgent for the government to take targeted measures to control deforestation and open up wasteland to protect the forest ecosystem.

Our study established a LUCC spatiotemporal evolution analysis method based on the GLC_FCS30 dataset, a driving mechanism analysis method based on principal components, and multiple linear stepwise regression analysis. This technical route can provide references for other countries and regions to carry out similar LUCC research. However, this method also suffers from the inability to quantify certain policy factors and the overly simplified process of modeling the drivers. In the future, we should further develop the framework and model methods for the study of spatialized and nonlinear LUCC driving mechanisms.

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Abbreviations

LUCC	Land use/land cover change
LUC	Land use/land cover
GLC_FCS30	Global Land-Cover product with Fine Classification System at 30 m
NRC	National Research Council
IGBP	International Geosphere-Biosphere Program
IHDP	International Human Dimensions Programme on Global Environmental Change
GLP	Global Land Programme
ICSU	International Council of Scientific Unions
ISSC	International Social Science Council
UNEP	United Nations Environment Programme
CCDC	Continuous Change Detection and Classification
PCA	Principal components analysis
FAO	Food and Agriculture Organization
PH	Phongsaly
LN	Luangnamtha
BK	Bokeo
OU	Oudomxay
LP	Luangprabang
HO	Huaphanh
XA	Xayaboury
VT	Vientiane Capital
XI	Xiengkhuang
VI	Vientiane
BL	Borikhamxay
KH	Khammuane
SV	Savannakhet
XB	Xaysomboon
SL	Saravan
XK	Xekong
CH	Champasack
AT	Attapeu

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