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Land-use change and urban expansion in Binh Duong province, Vietnam, from 1995 to 2020

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ABSTRACT
This study aims to analyze land-use change and urban expansion in Binh Duong province, Vietnam, from 1995 to 2020. Multitemporal Landsat images were used to develop land-use maps. Area statistics and transition matrices were employed to explore the land-use change; meanwhile, annual expansion rate (AER), expansion contribution rate (ECR), and district-, ring-, and sector-based analyses were employed to analyze the urban expansion. The results showed that there was a large transition from agricultural and unused lands to other uses. This resulted in an expansion of developed areas, recreational regions, mining sites, and water surfaces, a drastic decline of agricultural land for annual crops, and a fluctuation of perennial cropland and unused land. The study also indicated that the urban area has expanded 65 times within 25 years at an increasing rate. The AER and ECR were uneven between subregions, and there was a gradual expansion and shift from south to north of the province. The factors affecting the changes comprise natural conditions, development histories, policies and practices for urbanization, industrialization, and agricultural development, and product price fluctuations in the market. Practical lessons learned from this study could be useful for land planning and policymaking in other localities.

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Land-use change; urban expansion; change detection; spatiotemporal analysis; remote sensing

1. Introduction

Land-use change has various impacts on the environment and human life, such as run-off characteristics (Sajikumar and Remya 2015), landscape pattern (Zhang et al. 2010; Dadashpoor et al. 2019), land surface temperature (Zhang and Sun 2019), soil erosion (Nampak et al. 2018), as well as biodiversity and ecosystem services (Tolessa et al. 2017; Trisurat et al. 2019). Therefore, studies on land-use change are crucial to resource and environmental monitoring as well as land management policymaking (Nampak et al. 2018). Land-use changes are caused by both natural and anthropogenic factors (Serra et al. 2008; Msofe et al. 2019). In terms of anthropogenic factors, activities and policies relating to urban expansion, industrialization, agricultural development, and exploitation

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of natural resources strongly influence land-use change. Among them, urbanization and industrialization often lead to rapid, strong, and one-way transformation, especially in developing countries (Pham and Yamaguchi 2011; Kantakumar et al. 2016; Rimal et al. 2017; Fenta et al. 2017; Andrade-Núñez and Aide 2018; Cao et al. 2019; Sumari et al. 2020). However, the availability of accurate information on spatiotemporal land-use changes, urbanization status, urbanization rates, and their driving factors in localities is often untimely even though it is essential (Kantakumar et al. 2016).

Remote sensing (RS) is a reliable tool for land cover and land-use monitoring (Toure et al. 2018). RS databases are increasingly diverse in quantity and quality, meeting different needs. With easy access and acquisition of images, such as MODIS, Landsat, and Sentinel, research related to the interpretation of RS imagery has become proactive and cost effective. Moreover, the development of image processing and classification techniques has increasingly improved the accuracy of results (Lu et al. 2011; Shao and Lunetta 2012; Noi and Kappas 2017; Toure et al. 2018; Quan et al. 2020). The combination of RS and spatial analysis techniques in geographic information systems allows researchers to detect land cover and land-use change more easily and timely. This has been confirmed in many studies in the literature on a local (Wu et al. 2006; Rawat and Kumar 2015; Tadese et al. 2020), national (Sánchez-Cuervo et al. 2012; Schoeman et al. 2013; Xu et al. 2020), continental (Mertes et al. 2015; Netzel and Stepinski 2015) and global scale (Giri et al. 2013; Li et al. 2017).

Binh Duong province is a province located in the Southern Key Economic Zone of Vietnam. Over the past 25 years, Binh Duong has emerged as a typical area of rapid urbanization and industrialization. As a consequence, the land-use change took place dramatically. However, a study on spatiotemporal land-use change and urban expansion in Binh Duong is still a gap. Thus, it is necessary to study these issues in this area. Such study helps explore not only the pattern of land-use change and urban expansion but also the factors influencing these processes. From there, some practical experience can be learned for land-use planning and policymaking in other areas not only in Vietnam but also in other countries.

Therefore, this study aims to (1) explore the spatiotemporal dynamics of land-use in Binh Duong province from 1995 to 2020, (2) analyze the urban expansion and its orientation over the past 25 years, and (3) analyze the factors affecting the land-use change and urban expansion of Binh Duong province.

The rest of this paper is organized as follows. Section 2 introduces the study area. Section 3 describes the data and methods used. The results are reported in Section 4. In Section 5, a discussion and recommendation are given. Finally, the conclusions are presented in Section 6.

2. Study area

Binh Duong province is located in the Southeast region of Vietnam, covering approximately 2,694.64 km^2, with a total population of about 2.5 million as of 2019 (Binh Duong Statistical Office 2020). Administratively, as of 2020, the province was divided into five urban districts (also known as cities and towns) and four rural districts (Figure 1). Thu Dau Mot city is the administrative–economic–cultural centre of Binh Duong province.

Since its reestablishment in 1997, the urbanization and industrialization process of the province has been extremely rapid. In 1995, the urbanization rate, which was calculated as a percentage of the urban population per total population, accounted for only 17.51%; in 2019, the rate reached 79.86% (General Statistics Office of Vietnam 2020). The first

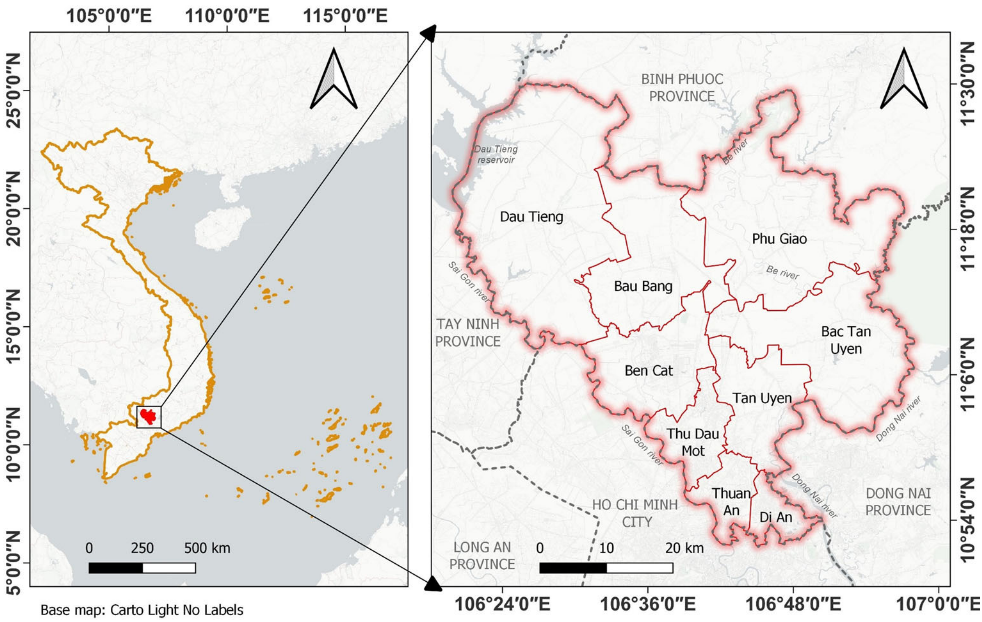

Figure 1. Study area.

industrial park, i.e. Song Than 1, was established in 1995. As of 2019, Binh Duong has 29 industrial parks and 12 industrial clusters, with an average occupancy rate of over 70% in which more than 90% of many of them have been filled. Binh Duong is currently considered the 'industrial capital' of Vietnam. The development of industry has considerably contributed to the economic development of the province. The gross regional domestic product at current prices increased from VND 3,915 billion in 1997 (industry and construction accounted for 50.4%) to VND 48,761 billion in 2010 (industry and construction accounted for 63%) and 360,797 billion in 2019 (industry and construction accounted for 66.77%) (Binh Duong Statistical Office 2016; Binh Duong Statistical Office 2020). Owing to the expansion of the urban and industrial areas as well as other human activities, the land cover, and land-use in the province have significantly changed over the past 25 years.

3. Material and methods

The overall workflow consisted of selection of time points and satellite images, preprocessing, generation of land use maps according to the method of Bui and Mucsi (2021), accuracy assessment, change detection, and urban expansion analysis. The classification steps for generating land-use maps were performed in ERDAS IMAGINE 2020 and R software; meanwhile, other analysis steps were performed in QGIS 3.10 software. The workflow is illustrated in Figure 2 and some highlights of the process followed are described below.

3.1. Selection of time points and satellite images

The Landsat level-2 surface reflectance images (projection: WGS 84/UTM Zone 48 N, path/row: 125/52) were employed in this study. The images were ordered and downloaded

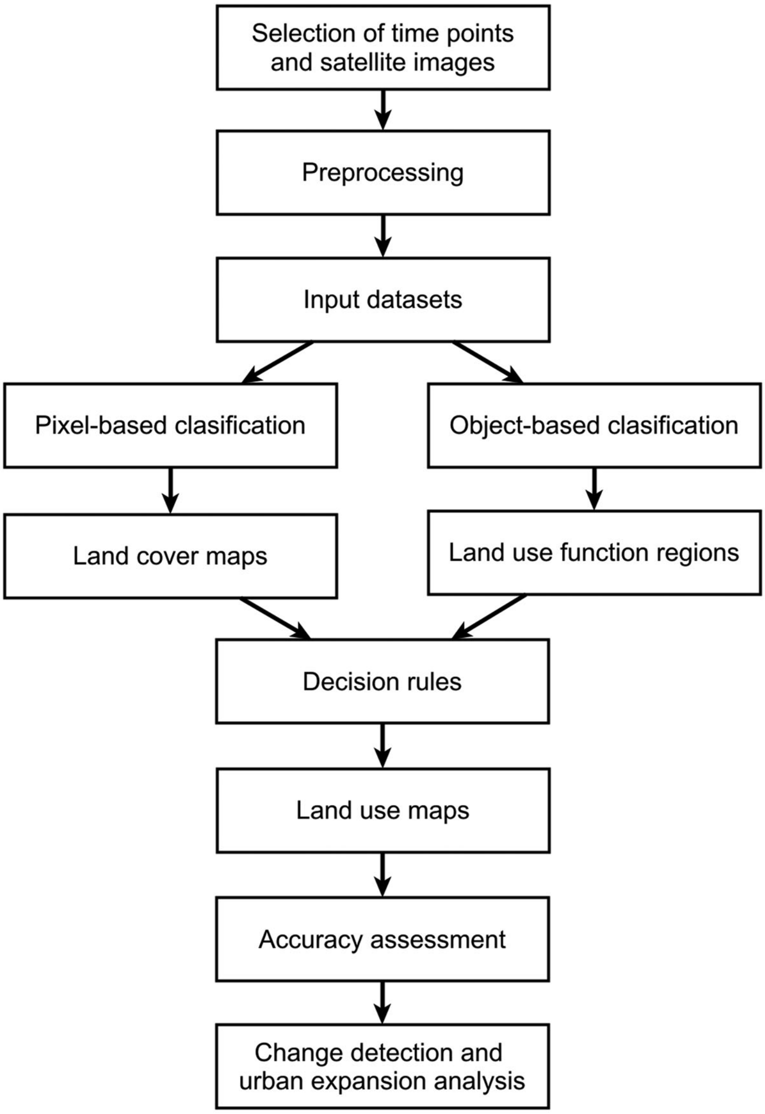

Figure 2. Overall workflow.

from the United States Geological Survey website (via the link: https://earthexplorer.usgs.gov/). A survey of the availability and quality of Landsat images from 1994 to 2020 (hereinafter, referenced years) in the study area was conducted to select suitable images and time points for the classification process. To generate the land-use map of each year, the method required at least two cloud-free images as the input for classification. Therefore, the criteria for selecting the time points and images included the following: (1) The images belong to Landsat-5, −7, or −8 sensors. (2) There is no error of scan-line corrector for the Landsat-7 images. (3) It is possible to collect or mosaic to create two cloud-free images in the same year or in two consecutive years. As a result, six referenced years were identified to create land-use maps: 1995, 2001, 2005, 2010, 2015, and 2020. The images used at each referenced year are listed in Table 1. No Landsat-7 image was selected because the three mentioned criteria were not met. In addition, except for 2001, most selected images were in the dry season.

Table 1. Summary of Landsat images used.

Time point	Acquired date	Sensor
1995	14-Nov-94	Landsat-5
	02-Feb-95	Landsat-5
2001	27-Sep-00	Landsat-5
	06-Nov-00	Landsat-5
	14-Nov-00	Landsat-5
	15-Apr-01	Landsat-5
	09-May-01	Landsat-5
2005	11-Dec-04	Landsat-5
	11-Feb-04	Landsat-5
	13-Feb-05	Landsat-5
2010	09-Dec-09	Landsat-5
	11-Feb-10	Landsat-5
2015	24-Jan-15	Landsat-8
	29-Mar-15	Landsat-8
	09-Feb-15	Landsat-8
2020	06-Jan-20	Landsat-8
	23-Feb-20	Landsat-8
	07-Feb-20	Landsat-8

3.2. Preprocessing

The Landsat images collected were level 2 images, which have been geocorrected, projected to WGS84 Zone 48 N, and converted to surface reflectance, so they were ready for use. In this study, bands 2, 3, 4, 5, 6, and 7 for Landsat 8 images and bands 1, 2, 3, 4, 5, and 7 for Landsat 5 images were used. The preprocessing steps included masking cloud, mosaicking, subsetting, and stacking. The administrative boundary data downloaded from the Database of Global Administrative Areas project website (via the link: https://gadm.org/) were used for the subsetting step. Each year, two subsetted images were stacked to create a multitemporal image with 12 bands. Then, these multitemporal images were used as input for the classification.

3.3. Generation of land-use maps

In this study, we employed a classification scheme and method proposed by Bui and Mucsi (2021) to generate land-use maps of Binh Duong province from 1995 to 2020. This is a hybrid approach, combining pixel-based and object-based classification with spatial analysis and decision rules, to generate a land-use map from multi-temporal Landsat images. This method has proven to be effective in generating highly accurate land-use maps in the study area.

For classification scheme, the main land-use types in the study can be classified into eight classes: unused land, industry and commerce, recreation and green space, mixed residence, mining sites, agriculture with annual plants, agriculture with perennial plants, and water surface. For the procedure, there are three main steps to produce a land-use map including pixel-based classification to generate land cover map (Step 1), object-based classification and spatial analysis to extract land-use function regions (Step 2), and the combination of the land cover map and function region in a set of decision rules to produce the final land-use map (Step 3). A detailed description can be found in the mentioned study.

During Steps 1 and 2, the random forest classifier was applied to both pixel- and objected-based classifications. The training data were collected based on the field survey between January and February 2020, Google Earth history images, and our personal experiences. For consistency, the parameters of mtry and ntree were set to default values at all classification rounds, i.e. the mtry was equal to the square root of the total number of variables, and the ntree was 500 trees. Further, a 3×3 majority filter was applied to reduce the 'salt-and-pepper' noise instead of the clump and eliminate in Step 1. Other parameters in this stage were set similar to the study of Bui and Mucsi (2021).

In addition, to increase the accuracy of results, several additional works were performed manually as follows: (1) Some land-use function regions were added manually after Step 2. They included the regions that could not be automatically formed due to some reasons, such as only accounting for a very small area insufficient for training and classification (e.g. industry and commerce regions in 1995, golf courses in 1995, 2001, 2005), being excluded after spatial analysis within Step 2 (e.g. small and discrete patches of recreation area and mining site), or being entertainment complexes (e.g. the Dai Nam wonderland and new city park). (2) A 30-m buffer was applied to the mining function regions in Step 2 to make their boundary precise. (3) In the land cover maps generated after Step 1, some easily observable areas where barren lands were misclassified into impervious surfaces were corrected. Consequently, six land-use maps for the six referenced years were developed.

3.4. Accuracy assessment

The accuracy of the extracted land-use maps was assessed based on the overall accuracy (OA), user's accuracy (UA), and producer's accuracy (PA). To collect the validation data, we applied the stratified random sampling method with a compromise approach proposed by Congalton and Green (2019). In each map, 1,000 points were generated randomly. Among them, the minimum points for each class were set to 50 points, and the other points were allocated proportionally to the area of each class. The advantage of this method is that it can ensure that the distribution of validation points was proportional to the area of each land-use type, whereas the PA and UA of the rare classes were statistically significant (Congalton and Green 2019). The generated points were then visually interpreted and labelled based on the Landsat images, Google Earth history images, and our personal experiences. The allocation of validation points in each map is listed in Table 2.

There is no common threshold for the acceptable accuracy rate in the literature because it depends on the purpose of the research (Congalton and Green 2019). In this study, we adopted the values given by Thomlinson et al. (1999) where OA was at least equal to 85% and PA and UA of classes were equal to or greater than 70%.

Table 2. Allocation of validation points (unit: points).

Class \ Year	1995	2001	2005	2010	2015	2020
Unused land	90	66	89	106	111	105
Industry & Commerce	50	51	53	59	65	75
Recreation & Green space	50	50	50	50	52	53
Mixed residence	51	55	62	70	80	100
Mining site	50	50	51	50	50	50
Agriculture with annual plants	171	158	129	83	72	70
Agriculture with perennial plants	474	504	502	514	502	480
Water surface	64	66	64	68	68	67
TOTAL	1000	1000	1000	1000	1000	1000

3.5. Change detection and urban sprawl analysis

Besides statistics on the area accounted for by each land-use type in each year, transition matrices were employed to assess the detailed 'from-to' change between land-use classes in different years. It is a common approach in land-use change studies to compare maps between different time points (Zhang et al. 2017). The rows of the transition matrix represent the land-use classes of the former time point (T1), whereas the columns represent the ones of the later time point (T2). The main diagonal elements indicate the landscape area that shows the persistence of class i. Off diagonal entries indicate a transition from class i in T1 to a different class j in T2.

Urban sprawl is defined as 'the spreading of urban developments (such as houses and shopping centres) on undeveloped land near a city' (Merriam-Webster 2022). Although some studies distinguished the terms 'urban expansion' and 'urban sprawl' (Amponsah et al. 2022; Pratama et al. 2022), most studies in the literature used the two terms with the same meaning. In this paper, we also used them interchangeably. To analyze the spatial and temporal processes of the urban expansion, the land-use maps were first reclassified into two: urban and nonurban. In this study, the urban area was considered as both mixed residential regions as well as industrial and commercial zones; meanwhile, other land-use types belonged to the nonurban area. Afterward, the annual expansion rate (AER) and expansion contribution rate (ECR) were calculated to measure the characteristics of the urban sprawl of each administrative unit of Binh Duong province. The metrics were defined by Kantakumar et al. (2016) as follows:

$$AER = \frac{B_{(i,t_2)} - B_{(i,t_1)}}{t_2 - t_1} \tag{1}$$

$$ECR = \frac{B_{(i,t_2)} - B_{(i,t_1)}}{B_{t_2} - B_{t_1}} \times 100\% \tag{2}$$

where AER is the annual urban expansion rate during the period (in km^2.year^{-1}), ECR is the percentage share of urban expansion of an individual administrative unit in the study area (in percent); $B_{(i,tj)}$ is the built-up area within administrative unit i at time t_j (in km^2), and B_{tj} is the total built-up area in the study area at time t_j.

In addition, we employed the ring- and sector-based analyses. A ring-based analysis is a spatial analysis based on concentric circles separated by a certain distance, meanwhile, a sector-based analysis is based on sectors (i.e. fan-shaped areas) that have the same central vertex but in different orientations. These approaches have proven their effectiveness in exploring the spatial distribution of urban areas in terms of distance and orientation relative to a predefined urban centre point (Yin et al. 2011; Jiao 2015; Peng et al. 2015; Rimal et al. 2017; Acheampong et al. 2018; Cao et al. 2019). Analyzing urban expansion in terms of distance and orientation is important because it can reveal the pattern of urbanization, and it also can reflect the impact of land-use planning and policies on the urbanization process. In these analyses, defining a place as the urban centre point is an essential requirement. We considered the Thu Dau Mot market as the urban centre. From this point, 32 buffer zones with a distance of 2 km and 16 sector fans with an angle of 22.5° were generated to measure the distance and orientation, respectively (Figure 3). After that, the buffer zones and sectors were overlaid with land-use maps. The urban area was then summarized in each buffer zone and sector.

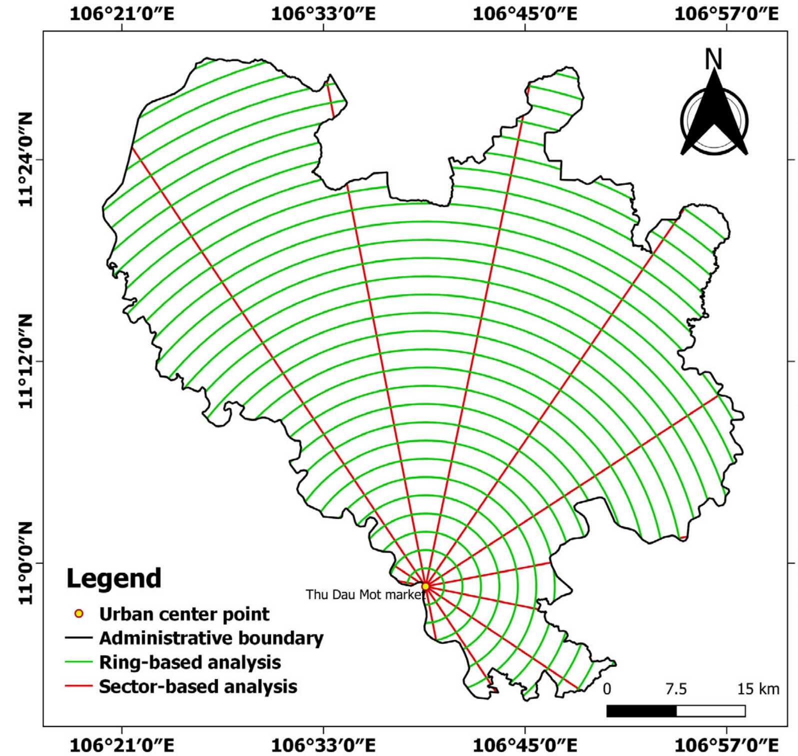

Figure 3. Ring- and sector-based analyses.

Table 3. Accuracy of extracted land-use maps.

Year / Class	1995		2001		2005		2010		2015		2020	
	PA (%)	UA (%)	PA (%)	UA (%)	PA (%)	UA (%)	PA (%)	UA (%)	PA (%)	UA (%)	PA (%)	UA (%)
L	70.8	75.6	80.0	78.8	73.3	83.1	82.7	81.1	87.5	88.3	80.2	88.6
IC	88.2	90.0	71.0	86.3	78.8	98.1	82.8	89.8	87.5	86.2	87.7	85.3
RG	95.9	94.0	97.3	72.0	91.7	88.0	95.9	94.0	98.1	98.1	90.2	86.8
MR	81.4	94.1	73.6	70.9	90.7	79.0	75.0	81.4	80.5	87.5	82.4	75.0
MS	92.6	100	94.2	98.0	96.2	98.0	96.0	96.0	100	98.0	98.0	96.0
AA	83.5	80.1	83.7	81.0	79.4	77.5	84.0	75.9	81.7	80.6	77.8	80.0
AP	93.7	91.4	93.9	94.2	95.1	92.4	95.3	94.9	96.8	96.2	94.0	94.6
WS	98.5	100	91.7	100	96.9	98.4	94.3	97.1	98.5	95.6	100	97.0
	OA = 89.2%		OA = 88.9%		OA = 89.6%		OA = 90.8%		OA = 93.0%		OA = 90.1%	

Note: OA = overall accuracy; PA = producer's accuracy; UA = user's accuracy; UL = Unused land; IC = Industry & Commerce; RG = Recreation & Green space; MR = Mixed residence; MS = Mining site; AA = Agriculture with annual plants; AP = Agriculture with perennial plants; WS = Water surface.

4. Results

4.1. Accuracy of extracted land-use maps

The OA of the extracted land-use maps in 1995, 2001, 2005, 2010, 2015, and 2020 were 89.2%, 88.9%, 89.6%, 90.8%, 93.0%, and 90.1%, respectively. The PA of the maps ranged from 70.8% to 100%, whereas the UA ranged from 70.9% to 100% (Table 3). These results showed that the maps are suitable for land-use change analyses.

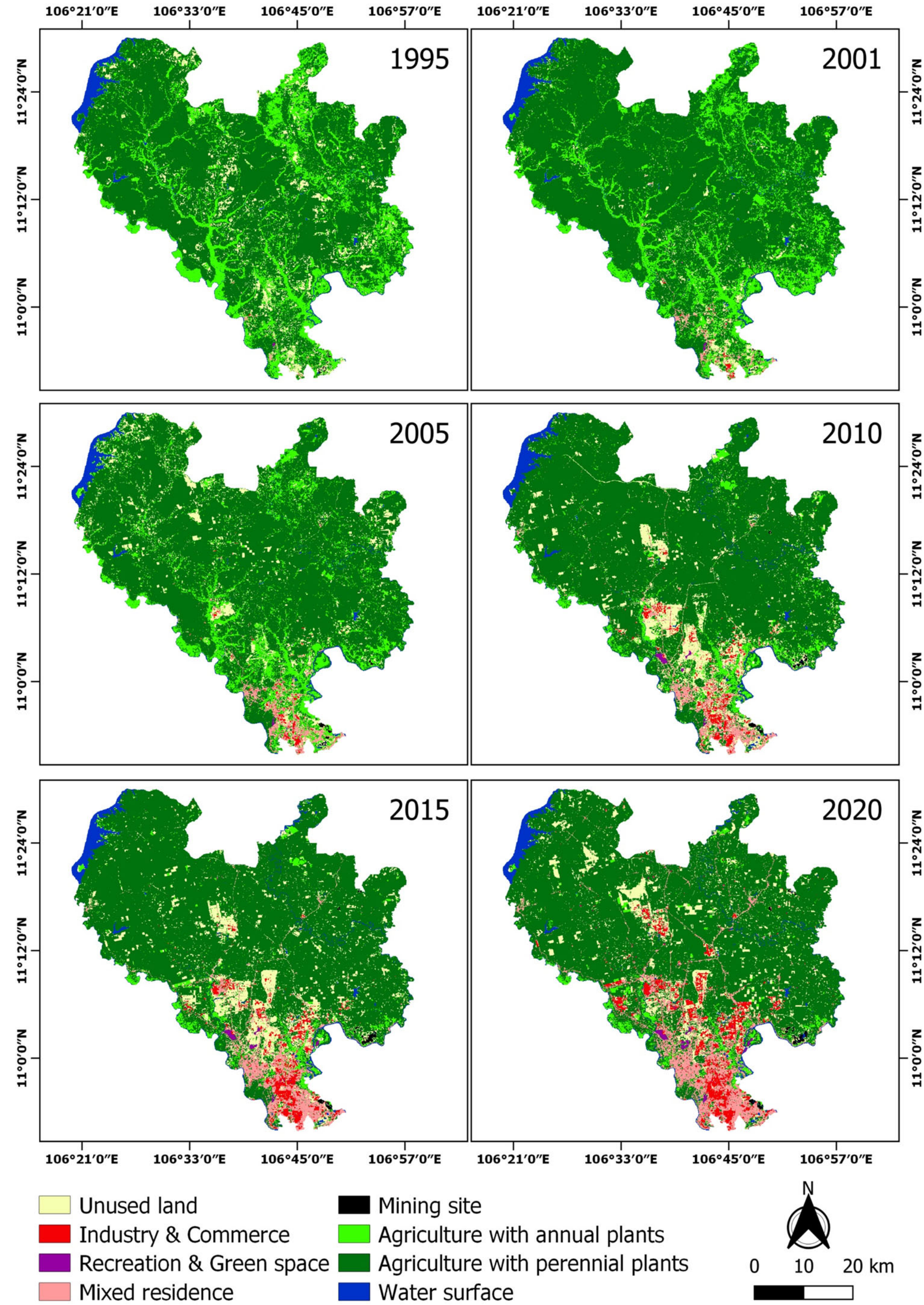

Figure 4. Land-use maps of Binh Duong province in the referenced years.

4.2. Land-use dynamics

The land-use maps in Binh Duong province at six time points are illustrated in Figure 4, and the detailed dynamics of each class from 1995 to 2020 are presented in Figure 5 and

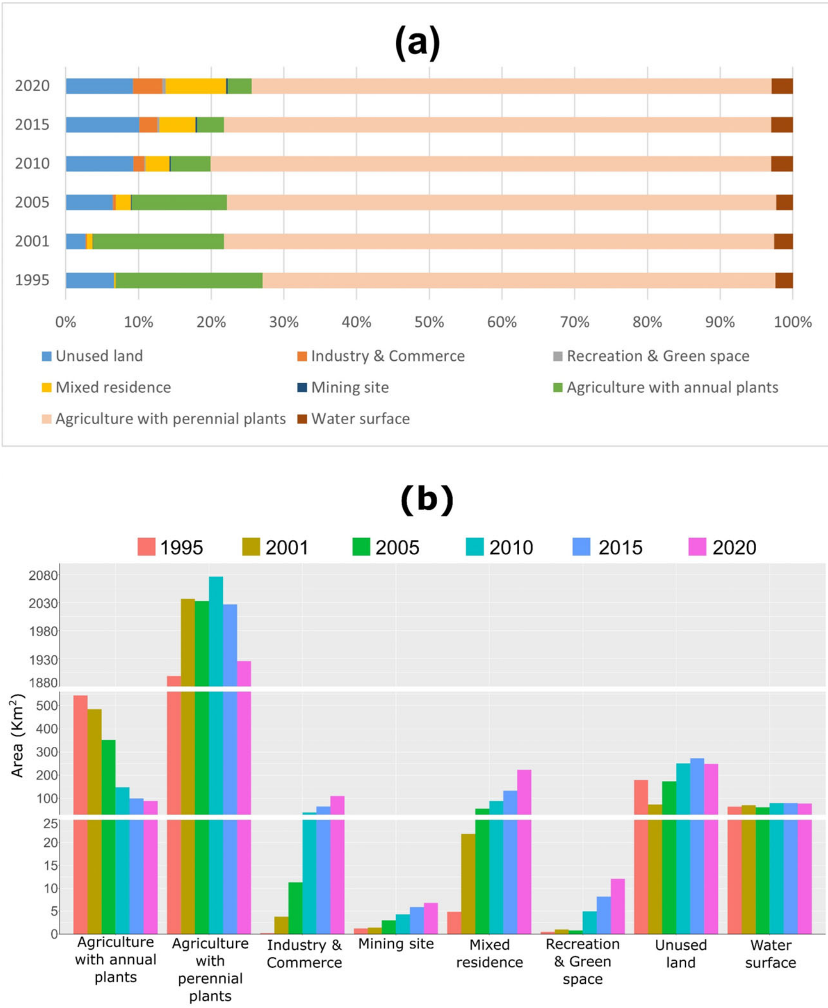

Figure 5. Dynamics of land-use in (a) proportion and (b) area.

Table 4. The annual change rate of each land-use type in each period (in km^2.year^{-1}).

Land-use type	1995–2001	2001–2005	2005–2010	2010–2015	2015–2020
Unused land	−17.6	25.0	15.4	4.4	−4.9
Industry & Commerce	0.6	1.9	5.7	5.2	8.9
Recreation & Green space	0.1	−0.1	0.8	0.6	0.8
Mixed residence	2.8	8.5	6.6	8.9	17.9
Mining site	0.0	0.4	0.2	0.3	0.2
Agriculture with annual plants	−10.0	−32.9	−40.9	−9.7	−2.2
Agriculture with perennial plants	23.0	−0.9	8.7	−9.9	−20.3
Water surface	1.0	−2.0	3.5	0.1	−0.3

Table 4. In addition, a transition matrix of land-use types between 1995 and 2020 was developed (Table 5).

In terms of spatial distribution, mixed residential areas, industrial and commercial zones, recreation areas, and quarries were concentrated in the south of the province, and the north was mainly agricultural land for perennial plants; meanwhile, the fields of

Table 5. Transition between land-use classes from 1995 to 2020 (in km^2).

	Transition								Summary		
2020 / 1995	UL	IC	RG	MR	MS	AA	AP	WS	Loss	Gain	Total loss/gain
UL	26.1	21.1	1.3	22.4	0.4	2.6	103.8	1.1	152.7	222.2	69.5
IC	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.1	109.9	109.7
RG	0.0	0.0	0.3	0.1	0.0	0.0	0.0	0.0	0.1	11.8	11.7
MR	0.1	0.6	0.0	4.0	0.0	0.0	0.1	0.0	0.9	218.8	217.9
MS	0.1	0.0	0.0	0.1	0.3	0.1	0.3	0.3	0.9	6.5	5.6
AA	40.1	17.9	2.6	48.1	3.4	59.1	357.9	14.7	484.8	29.5	−455.3
AP	181.5	69.9	7.9	147.8	2.7	25.9	1459.0	4.1	439.8	466.5	26.7
WS	0.3	0.2	0.1	0.2	0.0	1.0	4.3	58.1	6.1	20.2	14.1

Note: UL = Unused land; IC = Industry & Commerce; RG = Recreation & Green space; MR = Mixed residence; MS = Mining site; AA = Agriculture with annual plants; AP = Agriculture with perennial plants; WS = Water surface.

annual plants were mainly distributed along rivers, canals, and streams of the Sai Gon-Dong Nai river system. Agriculture with perennial plants was always the dominant class in the study area, with a proportion of 70.5% or more. In general, it is clear that from 1995 to 2020, a large amount of the agricultural land and unused land was converted to other uses. This conversion led to a strong change in the proportion between each land-use class over the past 25 years.

Between 1995 and 2020, there was a dramatic continuous upward trend in the mixed residential areas as well as industrial and commercial zones. In 1995, the area of mixed residence only accounted for 4.9 km^2. It rose to 21.9 km^2 in 2001, 133.5 km^2 in 2015, and 222.8 km^2 in 2020. Similarly, from occupying an area of only 0.2 km^2 in 1995, the industrial and commercial zones expanded to 11.3 km^2 in 2005 and 110.0 km^2 in 2020. As a result, the mixed residential areas as well as industrial and commercial zones expanded by a total of 217.9 and 109.7 km^2, respectively, within the 25 years. These expansions took about 217.7, 66.0, and 43.5 km^2 from perennial cropland, annual cropland, and unused land, respectively.

Although not as dramatic as the two built-up classes, the recreation, green space, and mining sites also had an uptrend in its area. From 1995 to 2005, the area of recreation and green space increased slightly from 0.5 to 0.8 km^2. After that, it increased rapidly to 12.1 km^2 in 2020. To tradeoff for this expansion, the areas of perennial plants, annual crops, and unused land reduced a total of 7.9, 2.6, and 1.3 km^2, respectively. Meanwhile, the mining sites experienced continuous growth from 1.2 km^2 in 1995 to 6.8 km^2 in 2020 for the 25 years. This expansion took a total of 6.5 km^2 from agricultural and unused land, whereas, since 2005, some quarries in Di An district have been closed permanently and converted to other land uses.

During the study period, 6.1 km^2 of water surface were occupied for other purposes, mainly for agricultural activities. Meanwhile, 20.2 km^2 of water surface were added, mainly from agricultural land, unused land, and mining sites. Consequently, although there was a fluctuation over time, the water surface area increased from 64.2 km^2 in 1995 to 78.3 km^2 in 2020.

Contrariwise, although supplemented by the conversion from other types, the area of agriculture with annual plants continuously decreased significantly over the 25 years. The area of annual plants reduced by 83.7%, from 543.9 km^2 in 1995 to 88.6 km^2 in 2020. From occupying more than 20% of the province's area, its proportion reduced to only 3.3%. In which, the nine-year period from 2001 to 2010 was the period that experienced the most dramatic decline. Meanwhile, the change in agricultural land for perennial plants can be categorized into two main trends: upward from 1995 to 2010 and downward from

2010 to 2020. The area increased from 1,898.8 km^2 in 1995 to 2,076.5 km^2 in 2010 before reducing to 1,925.5 km^2 in 2020. In addition to the conversion to other types of land-use, there was a transition between annual and perennial croplands over the studied period. About 357.9 km^2 of annual cropland was converted into perennial cropland from 1995 to 2020. Besides, about 25.9 km^2 of perennial croplands have been converted into annual croplands.

In terms of unused land, there was a fluctuation over the 25 years. Its area decreased from 1995 to 2001 and from 2015 to 2020; meanwhile, it increased from 2001 to 2015. In the 25 years, the total unused land area converted to other purposes was 152.7 km^2, mainly for re-cultivation and construction. In addition, 222.2 km^2 of other classes, mainly from agricultural land, were temporarily converted to unused land. Therefore, from accounting for 178.8 km^2 in 1995, Binh Duong province had approximately 248.3 km^2 of temporarily unused land in 2020.

4.3. Urban expansion analysis

The pattern of urban expansion in Binh Duong province is illustrated in Figure 6. The study result revealed that the developed area in Binh Duong province expanded rapidly, nearly 65 times, from 5.1 km^2 in 1995 to 332.8 km^2 in 2020. In addition, the gradual increase in the slope of segments in the line graph in Figure 6 indicates that the urban sprawl rate of the following period was always higher than that of the previous period. The AER increased from 3.4 km^2.year^{-1} in 1995–2001 to 6.9, 10.2, 11.8, and 22.3 km^2.year^{-1} in the periods of 2001–2005, 2005–2010, 2010–2015, and 2015–2020, respectively.

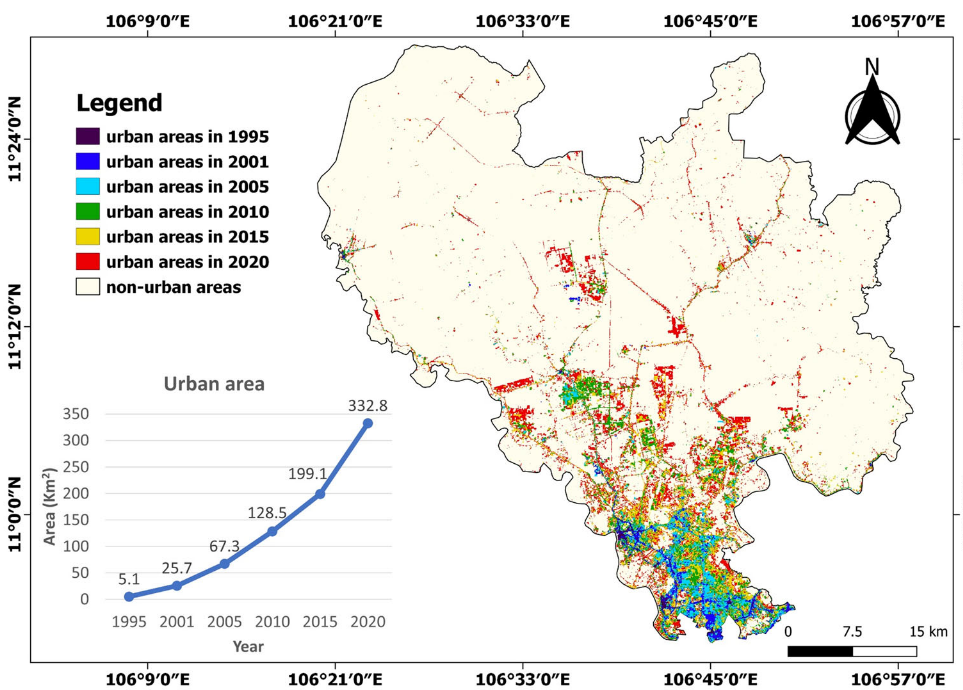

Figure 6. Urban expansion in Binh Duong province from 1995 to 2020.

Table 6. Annual expansion rate (AER in $km^2.y^{-1}$) and expansion contribution rate (ECR in percent) of districts.

		1995–2001		2001–2005		2005–2010		2010–2015		2015–2020	
District	Type	AER	ECR	AER	ECR	AER	ECR	AER	ECR	AER	ECR
Thu Dau Mot	Urban	0.6	16.2	0.9	8.6	2.5	20.2	2.9	20.8	3.5	13.3
Thuan An	Urban	1.1	33.0	4.1	39.2	2.1	16.8	3.0	21.4	2.0	7.5
Di An	Urban	1.3	38.1	3.1	29.9	1.6	13.4	2.3	16.0	1.0	3.7
Tan Uyen	Urban	0.2	5.9	1.2	11.1	1.7	14.3	3.6	25.3	6.0	22.4
Ben Cat	Urban	0.1	3.3	0.8	7.9	2.7	21.8	1.4	9.8	5.7	21.5
Phu Giao	Rural	0.0	0.2	0.2	1.5	0.3	2.2	0.3	2.2	2.2	8.1
Dau Tieng	Rural	0.0	0.7	0.1	0.7	0.3	2.8	0.1	0.5	1.5	5.5
Bau Bang	Rural	0.1	2.3	0.1	0.5	0.5	4.4	0.1	0.8	2.8	10.5
Bac Tan Uyen	Rural	0.0	0.3	0.1	0.7	0.5	4.1	0.5	3.3	2.0	7.6

However, the analysis result showed that the growth rate and contribution to the urban expansion among districts were not equal (Table 6) in each period. For urban districts, Di An and Thuan An districts had the highest two urbanization rates in the province from 1995 to 2005; their rates reached 3.1 and 4.1 $km^2.year^{-1}$, respectively. Thus, they were the main contributors to the urban expansion of the entire province in that period, with the ECR of each district ranging from about 30%–40%. However, in later periods, the urbanization rate of these two districts tended to decrease. Meanwhile, the AER of Tan Uyen, Ben Cat, and Thu Dau Mot gradually increased, and they shared, in turn, the top positions of main contributors from 2005 to 2020. In particular, the period of 2015–2020 witnessed an extremely rapid urban expansion of Tan Uyen and Ben Cat at an AER of approximately 6.0 $km^2.year^{-1}$, whereas the AERs of Di An and Thuan An decreased to within 1.0–2.0 $km^2.year^{-1}$. For rural districts, urban areas have only expanded significantly since 2015. The most significant was Bau Bang achieving an AER of 2.8 $km^2.year^{-1}$and an ECR of 10.5%, whereas other districts had an AER between 1.5 and 2.2 $km^2.year^{-1}$.

The results of the sector- and ring-based analysis were illustrated in Figures 7 and 8, respectively. Within 25 years, there has been a shift in the direction of urban expansion in the study area (Figure 7). From 1995 to 2015, the developed areas mainly expanded in the Southeast and East–Southeast directions from the urban centre point. However, since 2005, besides these two main directions, the urban area has been gradually expanded in the north and east directions, including Northwest, North–Northwest, North, North–Northeast, Northeast, East–Northeast, and East. Besides, from 2015 to 2020, the expansion to the north direction was stronger, whereas the expansion in the Southeast, East–Southeast, and East directions decreased significantly. Because this study was based on the administrative boundary, and Thu Dau Mot market––the predefined urban centre––was located on the east bank of the Saigon River, whereas the west bank was the Ho Chi Minh City, there was almost no urban development in the directions from South–Southwest to West–Northwest (in the clockwise direction).

In addition, urbanization occurred strongly within 22 km from the urban centre over the 25 years (Figure 8). This zone encompasses the centre area of Thu Dau Mot city within 4 km and the Thuan An, Di An, Tan Uyen, and Ben Cat districts within a distance of 6–22 km from the urban centre. The outward movement of peak value from the distance of 10 km to 14 km indicated that the urban areas expanded strongly in the direction of gradually moving away from the urban centre. Meanwhile, from the distance of 22 km onward, urbanization seemed to have only begun to accelerate since 2015, mainly in some central areas of the rural districts, yielding small peaks at distances of 26, 30, 40, and 46 km from the urban centre.

Overall, the results of the district-, sector-, and ring-based analyses clearly showed that urbanization gradually expanded and shifted from the south to the north of the province

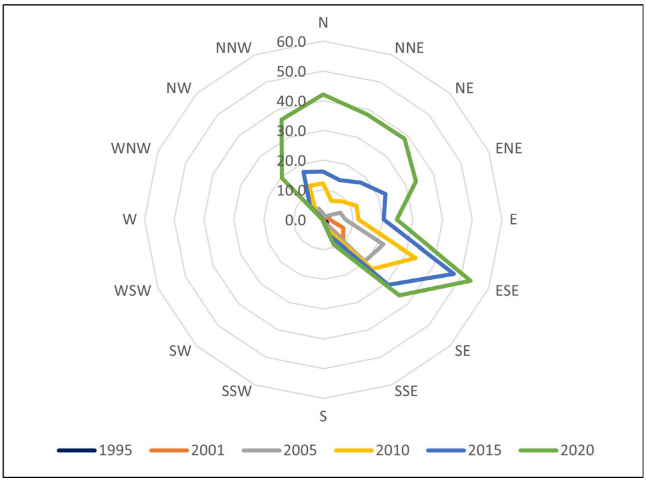

Figure 7. Spatial orientation of urban area from 1995 to 2020 (Units: km^2).

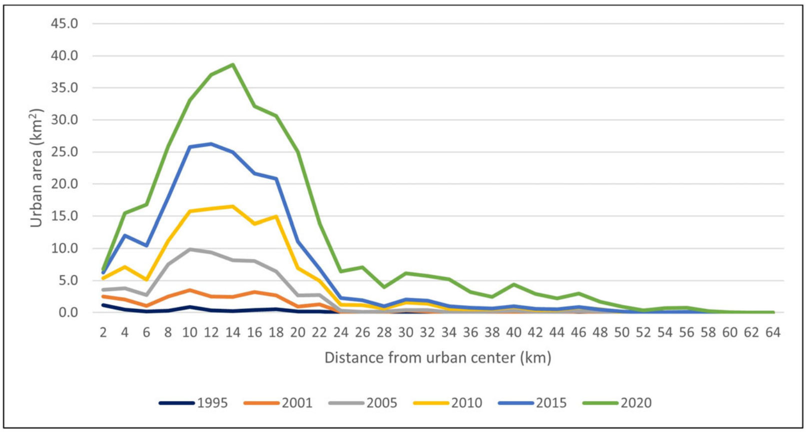

Figure 8. Variation in urban area by distance from urban centre from 1995 to 2020.

during the 25 years. Before 2005, urban expansion mainly took place in Thuan An, Di An, and southern Thu Dau Mot. In the periods after 2005, the urban expansion rate in the southern districts decreased because the industrial activities in these localities had stabilized, the districts were almost filled by mixed residential areas and industrial zones. Afterward, industrial zones and mixed residential areas rapidly expanded to Tan Uyen, Ben Cat, and northern Thu Dau Mot as well as spread to rural districts at an increasingly rapid rate.

5. Discussions

5.1. Factors affecting land-use change from 1995 to 2020

In summary, the common trends in land-use change over the 25 years in Binh Duong province is the conversion from agricultural land and unused land to other types of land-use. These changes are attributable to urbanization and industrialization, agricultural development policies and practices, natural conditions, and rubber price fluctuation. This section mainly discusses the factors causing the transition of agricultural land, unused land, water surface, mining activity, and recreational areas. The factors leading to rapid urban expansion in the province are discussed in Section 5.2.

Urbanization and industrialization are the primary causes of change. They lead not only to the inevitable expansion of built-up areas but also to other changes. These processes increase the demand for building materials for housing, industrial infrastructure, transportation systems, etc. (Schiller et al. 2020). Products of quarries in Binh Duong province serve the needs of not only the province but also neighbouring provinces. Consequently, although the mining activity may cause damages to the landscape, ecosystem, environmental quality, and health of people living around these areas (Bui et al. 2020; Vandana et al. 2020), the expansion of stone quarries occurred continuously during the 25 years. In addition, urban development includes not only the construction of residential, commercial, and industrial regions but also the establishment of amenity, relaxation, and leisure areas (Ty et al. 2014) as well as green space. In the period 1995–2005, there was only one recreation area, i.e. the Song Be golf course, and a few industrial parks. From 2005, many other recreation areas were formed, including the Dai Nam wonderland (2008), new city park (2009), Twin Dove golf course (2010), Harmonie golf course (2018), and Mekong golf course (2019). In addition, many new industrial parks were established and put into operation. The emergence of these areas caused the area of recreation and green space to increase rapidly. Overall, it can be observed that the majority area of the mentioned transition during the process of urbanization and industrialization is from agricultural land and unused land.

The changes in water surface area mainly came from the operation of the Dau Tieng reservoir, agricultural and aquacultural activities, hydrological regime, and the accumulation of rainfall water in exquarries. In addition, the construction of the Phuoc Hoa irrigation dam on Be River in the northern part of the province contributed to an increase in the water surface area since the 2010s. Phuoc Hoa Dam locates between Binh Duong and Binh Phuoc provinces and is connected to the Dau Tieng reservoir. This project has significant roles in supplying domestic and industrial uses and irrigation of more than 58,360 ha of agricultural land in Binh Duong, Binh Phuoc, Ho Chi Minh City, Tay Ninh, and Long An. Besides, the dam helps improve the environment and water quality in the downstream areas of the Sai Gon and Vam Co Dong rivers (Vu Van and Nguyen Hai 2015).

In addition to the conversion to other types of land-use, there was a transition between annual and perennial croplands over the studied period. In fact, the conversion from annual cropland into perennial cropland was mainly from low-yielding crops to higher-value perennial trees, such as rubber, pepper, cashew, and fruit trees, which were more favourable with the climate and soil of Binh Duong. Especially before 2011, owing to the continuous growth in demand for rubber leading to its price increase (Fox and Castella 2013; Hurni and Fox 2018), the conversion to rubber plantations was common in the northern part of the province. The expansion of rubber farms was also a general trend occurring in many other localities in Vietnam and Southeast Asia during this period. The rubber plantation area in Vietnam increased from 3,950 km^2 in 1999 to 5,500 km^2 in 2007 (Fox and Castella 2013), mainly in the central highlands and southern part. Meanwhile, in the entire Mainland Southeast Asia, 74,960 km^2 of land was converted to rubber farms from 2003 to 2014, of which 30% was conversions from low vegetations (mainly annual crops) (Hurni and Fox 2018). In addition, since 2010, the province has had an agricultural development planning policy until 2020, in which priority is given to the expansion of areas specialized in rubber, fruit trees, and safe vegetables. Therefore, the area planted with annual crops continued to be replaced by perennial crops (People's Committee of Binh Duong Province 2010; People's Committee of Binh Duong Province 2018). Meanwhile, the conversion from perennial croplands into annual croplands is mainly due to the impact of the sharp drop in rubber prices since 2011 (Hurni and Fox 2018). Many farmers have cut down their rubber plantations to grow short-term crops, mainly grass for animal husbandry. In addition, the agroforestry practices, i.e. the intercropping practices of the young rubber with annual crops such as legumes, corn, sesame rice, cassava, papaya, and bananas, are a factor increasing annual croplands in the classified maps. These issues are also found in other rubber-growing areas (Stroesser et al. 2018; Kusakabe and Chanthoumphone 2021; Huang et al. 2022; Su et al. 2022). In summary, the transition between annual and perennial croplands is due to the effects of agricultural development policies and practices, natural conditions, and product price fluctuations in the market.

In the study area, unused land is a type of land-use with special characteristics. It is considered as the intermediate class in the transition between other classes. Therefore, besides the variation in area, its spatial distribution is hardly fixed, especially in agricultural regions. The conversion to and from unused land comes from two main reasons: agricultural activities and planning of urban and industrial development. In the former, the agricultural land is often converted to unused land and then re-cultivated in a short time, which can easily be seen in between 1995 and 2001, as an example. In the latter, its behaviour is more complicated. The planned areas are levelled and converted into bare land (considered as temporarily unused land) to prepare for construction in the following stages. However, there is a fact in Vietnam that these areas may be quickly converted into built-up areas or remain as bare land for a long time depending on the development plan and investment progress. Therefore, the accumulation of this kind of 'unbuilt-up' bare land coupled with the emergence of new bare land areas for other reasons can cause the area of unused land to fluctuate over time.

5.2. Factors affecting urban expansion from 1995 to 2020

The orientation of urban development in Binh Duong found in this study clearly reflects the natural conditions and history of the province as well as the province's development policies and land-use planning.

First, Thu Dau Mot city, which is the urban centre of the province, is a long-established urban area on the banks of the Saigon River. Along with Thu Dau Mot, there are some towns developed in the south, such as Lai Thieu, Bung, and Di An. This area had favourable conditions for urbanization and industrialization such as its location near Ho Chi Minh City, convenient rail, and road traffic, a long history of urban development, commercial activities and handicrafts, and dense population (Le 2019). Therefore, after re-establishing the province in 1997, the provincial government focused on urbanization and industrialization in the southern region, including Thu Dau Mot, Thuan An, and Di An (Party Committee of Binh Duong Province 1997; Party Committee of Binh Duong Province 2001).

Second, since 2007, the government has, in turn, issued decisions on the master plan for socio-economic development and urban development of Binh Duong province until 2020, with a vision for 2030 (Prime Minister of Vietnam 2007; People's Committee of Binh Duong Province 2012; Prime Minister of Vietnam 2014), to upgrade Binh Duong into a centrally-controlled city (as known as a municipality, Vietnamese: thành phố trực thuộc trung ương) in the period 2020–2030. With the orientation to become an 'industrial metropolis' and develop evenly based on a regional strategy to reduce the imbalance in urban distribution, the provincial government has expanded the distribution of industrial zones to the north. Accordingly, the Binh Duong metropolis is divided into three subregions: (1) Southern urban region (Di An, Thuan An): compact urban model, high density. (2) Central urban region (Thu Dau Mot, Ben Cat, Tan Uyen): multifunctional and multicentre model, medium density. The administrative-political centre is moved to the new urban area of Hoa Phu–Phu Tan (as known as the Binh Duong new city) in the north of Thu Dau Mot, located in the Binh Duong Industrial–Service–Urban Complex. (3) Northern urban region (the other districts): satellite urban model, low density. Under these policies, the urban and industrial areas in Binh Duong gradually expanded to the north in latter periods.

Third, the increasing urbanization rate of the province stems from industrialization. In addition to the master plans, a series of flexible policies have been implemented by the provincial government for industrial development. They comprise policies on land acquisition, development of transport systems and industrial infrastructure, reform of administrative procedures, attraction of investment capital, and attraction of human resources (Le 2019; Le et al. 2019; Nguyen et al. 2019; Do et al. 2020). These policies can be briefly summarized as follows: (1) accelerating the land clearance and conversion from agricultural land to urban and industrial land by policies on resettlement, vocational training, and job creation for people whose land has been acquired; (2) simplifying administrative procedures to attract domestic and foreign investment to industrial parks; (3) mobilizing nonbudget capital to develop the infrastructure of industrial zones and improve the transport system based on the build-operate-transfer model; (4) implementing policies on housing and social benefits for workers. These policies have created a favourable investment environment and confidence for investors. As a result, investment capital into the province continuously increased. The total foreign direct investment capitals in the periods of 2001–2005, 2006–2010, and 2010–2015 were USD 1.8 billion, 5.7 billion, and 10.2 billion, respectively, in which investment capital in industrial zones accounted for 90% (Binh Duong Statistical Office 2016). In consequence, many projects have been invested, new factories have been continuously formed and expanded. Since the first industrial park was established in 1995, as of 2019, Binh Duong has 29 industrial parks and 12 industrial clusters, with an average occupancy rate of over 70% in which many of them have been filled over 90%.

Last, as a result of the mentioned policies, the industrial development in the province created a job market with high and stable income. The monthly average income per capita at current prices of Binh Duong province and the Southeast region is higher than that of other regions of Vietnam (Table 7). People tend to migrate from low- to high income

Table 7. Monthly income per capita at current prices of Binh Duong province, economic regions, and the whole country of Vietnam (in thousand VND).

Year / Region	1999	2010	2019
Binh Duong province	no data	2698	7433
Southeast	571	2304	6280
Whole country of Vietnam	295	1387	4295
Mekong River Delta	342	1247	3886
Central Highlands	345	1088	3095
North Central area and Central coastal area	229	1018	3331
Red River Delta	282	1580	5191
Northern midlands and mountain areas	199	905	2640

Source: General Statistics Office of Vietnam (2021).

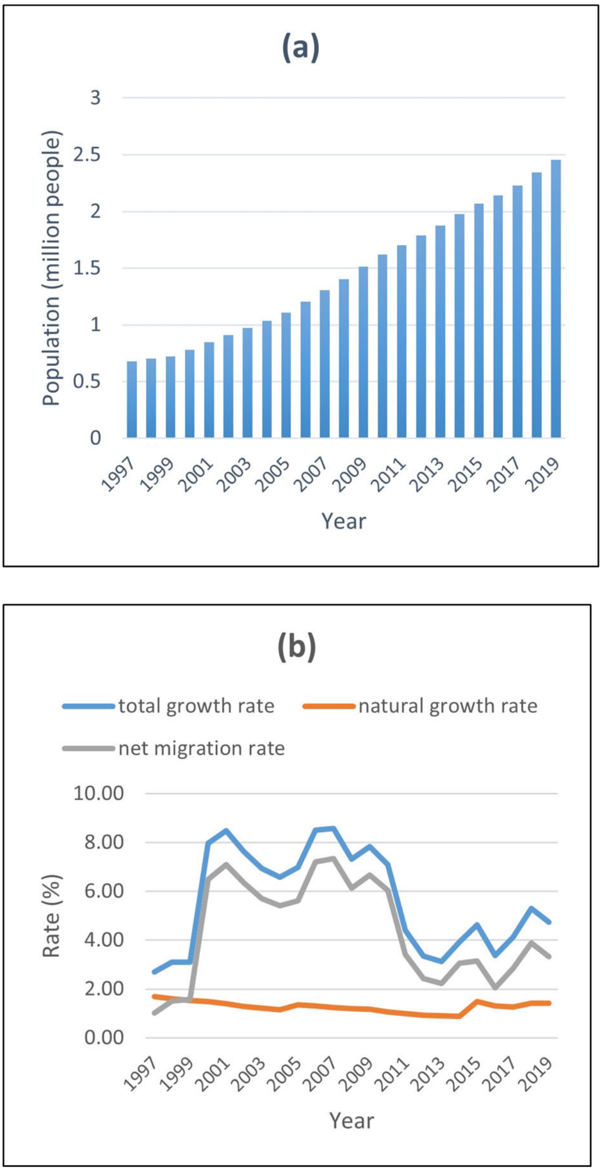

Figure 9. (a) Population growth and (b) growth rate in Binh Duong province (1997–2019).

areas (Phan and Coxhead 2010). Career opportunities with high income combined with housing and social benefits have led to not only the movement of people from rural to urban areas within the province but also the migration of foreigners (Figure 9), thereby increasing the population. Industrial development and population growth increased the demand for housing, transportation, and other utilities, creating a force for the expansion of mixed residential areas and other facilities. Since 2002, with the explosion of urban migration, the provincial government first implemented the concept of industrial park development in association with mixed residential areas and utilities for the planning of My Phuoc industrial park. This concept was then widely applied to the planning of urban and industrial zones in later stages.

Overall, the pattern of urban expansion in Binh Duong from 1995 to 2020 is the gradual transition from a compact urban form to a dispersed urban form, which is also found in many other cities in developing regions (Marengo 2015; Sumari et al. 2019; Xu et al. 2019; Xu et al. 2019). This pattern is the result of the combined effects of natural conditions, history, economic development, demographics, land-use and urban planning, and policies. These findings are consistent with the results of many studies on urban sprawl in cities around the world (Reilly et al. 2009; Mahendra and Seto 2019; Shao et al. 2021; Mahtta et al. 2022). Of which, either population growth or economic growth was often considered the main driver for urban expansion, depending on the regional variations (Mahendra and Seto 2019; Mahtta et al. 2022). For Binh Duong, the importance of these two drivers changes over time. This is consistent with the findings of Mahtta et al. (2022) when they studied the role of population and economic growth in urban land expansion in more than 300 cities between 1970 and 2014. The authors revealed that although population growth was the primary driver, the effect of economic growth has increased significantly in importance since 2000, especially in low-income, low-middle-income, and upper-middle-income countries. They also stated that this increase occurred up to a point. Population growth, mainly due to migration, would again be an important driver since a country entered the highest income category. This is what happened in Binh Duong during the study period although only on a local scale.

5.3. Take-away for practice

Some practical experience, which may help in land planning and policymaking for other localities, can be learned from the pattern of land use change and urban sprawl in Binh Duong province as follow.

- Besides having good land-use and urban planning, focusing on infrastructure development, investment attraction, and human resources attraction are essential factors to accelerate the process of industrialization and urbanization.
- Despite rapid urbanization, inefficient land use (i.e. unused land) remains a dilemma. Measures to accelerate the progress of projects to increase the efficiency of urban land use are necessary.
- Urbanization often leads to an impact on the real estate market and causes housing prices to increase rapidly. This issue needs to be regulated.
- The rapid increase in housing prices due to urbanization along with fluctuations in agricultural market prices can have a negative impact on the land-use practices of farmers. It is necessary to regulate these issues to limit the conversion of land use purposes or the conversion of crops to follow short-term market trends.

6. Conclusion

Although the information on spatiotemporal land-use change and urbanization status is necessary for land-use planning and decisionmaking, it is still lacking in many urban regions, especially emerging urban areas such as Binh Duong province of Vietnam. By using land-use maps extracted from multitemporal Landsat images and spatial analysis techniques, the spatiotemporal pattern of land-use change and urban expansion in Binh Duong province from 1995 to 2020 were analyzed in this study.

The research results showed that there were different trends in the area variation of land-use types, and there was a large transition from agricultural and unused land to other types of land-use within 25 years. This study also revealed that the urban area of the province expanded 65 folds within the 25 years at an increasing rate. The expansion rates were uneven between subregions, and there was a gradual expansion and shift from south to north of the province and spreading to rural districts at an increasingly rapid rate during the study period. It led to a gradual transition from a compact urban form to a dispersed urban form. The factors affecting land-use change and urban expansion of Binh Duong province were also discussed. They comprise the natural conditions, development history, policies and practices for urbanization, industrialization, and agricultural development, and fluctuation in the prices of products in the market.

The results of this study reveal a pattern of rapid urbanization in developing countries under the impact of land policies. Some practical lessons can be drawn from them. They can lay the groundwork for further studies on urban planning, land management, and policymaking in other localities not only in Vietnam but also in other countries. Further, land-use change can also cause adverse effects on the quality of the environment, landscape, and human health. Further studies on these issues are required.

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

Acheampong M, Yu Q, Enomah LD, Anchang J, Eduful M. 2018. Land use/cover change in Ghana's oil city: Assessing the impact of neoliberal economic policies and implications for sustainable fevelopment goal number one – A remote sensing and GIS approach. Land Use Policy. 73:373–384.

Amponsah O, Blija DK, Ayambire RA, Takyi SA, Mensah H, Braimah I. 2022. Global urban sprawl containment strategies and their implications for rapidly urbanising cities in Ghana. Land Use Policy. 114: 105979.

Andrade-Núñez MJ, Aide TM. 2018. Built-up expansion between 2001 and 2011 in South America continues well beyond the cities. Environ Res Lett. 13(8):84006.

Binh Duong Statistical Office. 2016. Binh Duong - 20 years of construction and development. Binh Duong (Vietnam).
Binh Duong Statistical Office. 2020. Statistical yearbook of Binh Duong 2019. Binh Duong (Vietnam).
Bui DH, Mucsi L. 2021. From land cover map to land use map: a combined pixel-based and object-based approach using multi-temporal landsat data, a random forest classifier, and decision rules. Remote Sens. 13(9):1700.
Bui LT, Nguyen PH, Nguyen DCM. 2020. Model for assessing health damage from air pollution in quarrying area – Case study at Tan Uyen quarry, Ho Chi Minh megapolis, Vietnam. Heliyon. 6(9):e05045.
Cao H, Liu J, Chen J, Gao J, Wang G, Zhang W. 2019. Spatiotemporal patterns of urban land use change in typical cities in the Greater Mekong Subregion (GMS). Remote Sens. 11(7):801.
Congalton R G, Green K. 2019. Assessing the accuracy of remotely sensed data principles and practices, 3rd ed. Boca Raton: CRC Press.
Dadashpoor H, Azizi P, Moghadasi M. 2019. Land use change, urbanization, and change in landscape pattern in a metropolitan area. Sci Total Environ. 655:707–719.
Do QC, Le NH, Hoang XD. 2020. From industrial policy to economic and social upgrading in Vietnam. Singapore: Singa.
Fenta AA, Yasuda H, Haregeweyn N, Belay AS, Hadush Z, Gebremedhin MA, Mekonnen G. 2017. The dynamics of urban expansion and land use/land cover changes using remote sensing and spatial metrics: the case of Mekelle City of northern Ethiopia. Int J Remote Sens. 38(14):4107–4129.
Fox J, Castella JC. 2013. Expansion of rubber (*Hevea brasiliensis*) in Mainland Southeast Asia: what are the prospects for smallholders? J Peasant Stud. 40(1):155–170.
General Statistics Office of Vietnam. 2020. Population [Internet]. [accessed 2020 Dec 8]. https://www.gso.gov.vn/en/population/.
Giri C, Pengra B, Long J, Loveland TR. 2013. Next generation of global land cover characterization, mapping, and monitoring. Int J Appl Earth Obs Geoinf. 25:30–37.
Huang IY, James K, Thamthanakoon N, Pinitjitsamut P, Rattanamanee N, Pinitjitsamut M, Yamklin S, Lowenberg-DeBoer J. 2022. Economic outcomes of rubber-based agroforestry systems: a systematic review and narrative synthesis. Agroforest Syst [Internet] :1–20.
Hurni K, Fox J. 2018. The expansion of tree-based boom crops in mainland Southeast Asia: 2001 to 2014. J Land Use Sci. 13(1–2):198–219.
Jiao L. 2015. Urban land density function: A new method to characterize urban expansion. Landsc Urban Plan. 139:26–39.
Kantakumar LN, Kumar S, Schneider K. 2016. Spatiotemporal urban expansion in Pune metropolis, India using remote sensing. Habitat Int. 51:11–22.
Kusakabe K, Chanthoumphone C. 2021. Transition from subsistence agriculture to rubber plantations in northern laos: analysis of household livelihood strategies by ethnicity and gender. SAGE Open. 11(2):215824402110114.
Le VH. 2019. The process of urbanization in Binh Duong province 1986–2010 (Vietnamese). Ho Chi Minh City, Vietnam: Vietnam National University-HoChiMinh City – University of Social Sciences and Humanities.
Le VN, Truong HT, Ton Nu QT, Le VH, Nguyen NK. 2019. Binh Duong urbanization in the period 1997–2017 (Vietnamese). Binh Duong, Vietnam: Thu Dau Mot University.
Li X, Chen G, Liu X, Liang X, Wang S, Chen Y, Pei F, Xu X. 2017. A new global land-use and land-cover change product at a 1-km Resolution for 2010 to 2100 based on human–environment interactions. Ann Am Assoc Geogr. 107(5):1040–1059.
Lu D, Li G, Moran E, Dutra L, Batistella M. 2011. A comparison of multisensor integration methods for land cover classification in the Brazilian Amazon. GIScience Remote Sens. 48(3):345–370.
Mahendra A, Seto KC. 2019. Upward and outward growth: managing urban expansion for more equitable cities in the global south. Work Pap.
Mahtta R, Fragkias M, Güneralp B, Mahendra A, Reba M, Wentz EA, Seto KC. 2022. Urban land expansion: the role of population and economic growth for 300+ cities. Npj Urban Sustain. 2(1):5.
Marengo MC. 2015. Sprawl and density, towards a dispersed urban form the case of Córdoba City – Argentina. JEA. 3(2):45–56.
Merriam-Webster. 2022. Urban sprawl. Merriam-Webster.com Dict. [accessed 2022 Jul 15]. https://www.merriam-webster.com/dictionary/urbansprawl
Mertes CM, Schneider A, Sulla-Menashe D, Tatem AJ, Tan B. 2015. Detecting change in urban areas at continental scales with MODIS data. Remote Sens Environ. 158:331–347.
Msofe NK, Sheng L, Lyimo J. 2019. Land use change trends and their driving forces in the Kilombero valley Floodplain, Southeastern Tanzania. Sustain. 11(2):505.

Nampak H, Pradhan B, Mojaddadi Rizeei H, Park HJ. 2018. Assessment of land cover and land use change impact on soil loss in a tropical catchment by using multitemporal SPOT-5 satellite images and Revised Universal Soil Loss Equation model. Land Degrad Develop. 29(10):3440–3455.
Netzel P, Stepinski TF. 2015. Pattern-based assessment of land cover change on continental scale with application to NLCD 2001–2006. IEEE Trans Geosci Remote Sens. 53(4):1773–1781.
Nguyen VH, Ton Nu QT, Nguyen VS, Le VH, Truong TT, Nguyen TTH, Nguyen TXT, Nguyen NK. 2019. Context of urbanization in Binh Duong (Vietnamese). Binh Duong, Vietnam: Thu Dau Mot University.
Noi PT, Kappas M. 2017. Comparison of random forest, k-nearest neighbor, and support vector machine classifiers for land cover classification using sentinel-2 imagery. Sensors (Switzerland). 18(1):18.
Party Committee of Binh Duong Province. 1997. Documents of the 6th congress of the party committee of Binh Duong Province (Vietnamese). Binh Duong (Vietnam).
Party Committee of Binh Duong Province. 2001. Documents of the 7th congress of the party committee of Binh Duong Province (Vietnamese). Binh Duong (Vietnam).
Peng W, Wang G, Zhou J, Zhao J, Yang C. 2015. Studies on the temporal and spatial variations of urban expansion in Chengdu, western China, from 1978 to 2010. Sustain Cities Soc. 17:141–150.
People's Committee of Binh Duong Province. 2010. Decision No. 4614/QD-UBND on approving the development planning of agriculture, forestry and fishery in Binh Duong province until 2020 (Vietnamese). Vietnam.
People's Committee of Binh Duong Province. 2012. Decision No. 1701/QD-UBND on approving the general planning project to develop Binh Duong metropolis until 2020, vision to 2030 (Vietnamese). Vietnam.
People's Committee of Binh Duong Province. 2018. Decision No. 157/QD-UBND on approving the adjustment of the planning for the development of agriculture, forestry, and fishery in Binh Duong province until 2020, supplementing the planning to 2025 (Vietnamese). Vietnam.
Pham HM, Yamaguchi Y. 2011. Urban growth and change analysis using remote sensing and spatial metrics from 1975 to 2003 for Hanoi, Vietnam. Int J Remote Sens. 32(7):1901–1915.
Phan D, Coxhead I. 2010. Inter-provincial migration and inequality during Vietnam's transition. J Dev Econ. 91(1):100–112.
Pratama AP, Yudhistira MH, Koomen E. 2022. Highway expansion and urban sprawl in the Jakarta Metropolitan Area. Land Use Policy. 112:105856.
Prime Minister of Vietnam. 2007. Decision No. 81/2007/QD-TTg on approving the master plan for socio-economic development of Binh Duong province until 2020 (Vietnamese). Vietnam.
Prime Minister of Vietnam. 2014. Decision No. 893/QD-TTg on approving the adjustment of the master plan for socio-economic development of Binh Duong province until 2020, supplementing the planning to 2025 (Vietnamese). Vietnam.
Quan Y, Tong Y, Feng W, Dauphin G, Huang W, Xing M. 2020. A novel image fusion method of multi-spectral and sar images for land cover classification. Remote Sens. 12(22):3801–3825.
Rawat JS, Kumar M. 2015. Monitoring land use/cover change using remote sensing and GIS techniques: A case study of Hawalbagh block, district Almora, Uttarakhand, India. Egypt J Remote Sens Sp Sci. 18(1):77–84.
Reilly MK, O'Mara MP, Seto KC. 2009. From Bangalore to the Bay Area: Comparing transportation and activity accessibility as drivers of urban growth. Landsc Urban Plan. 92(1):24–33.
Rimal B, Zhang L, Keshtkar H, Wang N, Lin Y. 2017. Monitoring and modeling of spatiotemporal urban expansion and land-use/land-cover change using integrated Markov chain cellular automata model. IJGI. 6(9):288.
Sajikumar N, Remya RS. 2015. Impact of land cover and land use change on runoff characteristics. J Environ Manage. 161:460–468.
Sánchez-Cuervo AM, Aide TM, Clark ML, Etter A. 2012. Land cover change in Colombia: surprising forest recovery trends between 2001 and 2010. PLoS One. 7(8):e43943.
Schiller G, Bimesmeier T, Pham ATV. 2020. Method for quantifying supply and demand of construction minerals in urban regions-A case study of hanoi and its Hinterland. Sustain. 12(11):4358.
Schoeman F, Newby TS, Thomson MW, Van den Berg EC. 2013. South African national land-cover change map. South African J Geomatics. 2(2):94–105.
Serra P, Pons X, Saurí D. 2008. Land-cover and land-use change in a Mediterranean landscape: A spatial analysis of driving forces integrating biophysical and human factors. Appl Geogr. 28(3):189–209.
Shao Y, Lunetta RS. 2012. Comparison of support vector machine, neural network, and CART algorithms for the land-cover classification using limited training data points. ISPRS J Photogramm Remote Sens. 70:78–87.

Shao Z, Sumari NS, Portnov A, Ujoh F, Musakwa W, Mandela PJ. 2021. Urban sprawl and its impact on sustainable urban development: a combination of remote sensing and social media data. Geo-Spatial Inf Sci. 24(2):241–255.

Stroesser L, Penot É, Michel I, Tongkaemkaew U, Chambon B. 2018. Income diversification for rubber farmers through agroforestry practices. how to withstand rubber price volatility in Phatthalung Province, Thailand. Rev Int Des Études du Développement. 235(3):117–145.

Su Y, Sujakhu NM, Smith A. 2022. Gendered impacts of falling rubber prices: Changing livelihood strategies in China's rubber hearltand. ICRAF Work Pap.

Sumari NS, Cobbinah PB, Ujoh F, Xu G. 2020. On the absurdity of rapid urbanization: Spatio-temporal analysis of land-use changes in Morogoro, Tanzania. Cities. 107:102876.

Sumari NS, Xu G, Ujoh F, Korah PI, Ebohon OJ, Lyimo NN. 2019. A geospatial approach to sustainable urban planning: lessons for Morogoro Municipal Council, Tanzania. Sustain. 11(22):6508.

Tadese M, Kumar L, Koech R, Kogo BK. 2020. Mapping of land-use/land-cover changes and its dynamics in Awash River Basin using remote sensing and GIS. Remote Sens Appl Soc Environ. 19(June):100352.

Thomlinson JR, Bolstad PV, Cohen WB. 1999. Coordinating methodologies for scaling landcover classifications from site-specific to global: steps toward validating Global Map products. Remote Sens Environ. 70(1):16–28.

Tolessa T, Senbeta F, Kidane M. 2017. The impact of land use/land cover change on ecosystem services in the central highlands of Ethiopia. Ecosyst Serv. 23:47–54.

Toure SI, Stow DA, Shih HC, Weeks J, Lopez-Carr D. 2018. Land cover and land use change analysis using multi-spatial resolution data and object-based image analysis. Remote Sens Environ. 210: 259–268.

Trisurat Y, Shirakawa H, Johnston JM. 2019. Land-use/land-cover change from socio-economic drivers and their impact on biodiversity in Nan Province, Thailand. Sustain. 11(3):649.

Ty PH, Phuc NQ, Westen G v 2014. Vietnam in the debate on land grabbing: conversion of agricultural land for urban expansion and hydropower development. In: Kaag M, Zoomers A, editors. The global land grab: beyond the hype. 1st ed. Nova Scotia: Fernwood Publishing; p. 135–151. http://www.bloomsburycollections.com/book/the-global-land-grab-beyond-the-hype/ch8-vietnam-in-the-debate-on-land-grabbing-conversion-of-agricultural-land-for-urban-expansion-and-hydropower-development/.

Vandana M, John SE, Maya K, Padmalal D. 2020. Environmental impact of quarrying of building stones and laterite blocks: a comparative study of two river basins in Southern Western Ghats, India. Environ Earth Sci. 79(14):1–15.

Vu Van N, Nguyen Hai A. 2015. Assessment of the water transfer capacity from Be River Basin through Phuoc Hoa Hydraulic-Works. Clean Soil Air Water. 43(5):645–651.

Wu Q, Li H q, Wang R s, Paulussen J, He Y, Wang M, Wang B h, Wang Z. 2006. Monitoring and predicting land use change in Beijing using remote sensing and GIS. Landsc Urban Plan. 78(4):322–333.

Xu G, Dong T, Cobbinah PB, Jiao L, Sumari NS, Chai B, Liu Y. 2019. Urban expansion and form changes across African cities with a global outlook: Spatiotemporal analysis of urban land densities. J Clean Prod. 224:802–810.

Xu G, Jiao L, Liu J, Shi Z, Zeng C, Liu Y. 2019. Understanding urban expansion combining macro patterns and micro dynamics in three Southeast Asian megacities. Sci Total Environ. 660:375–383.

Xu X, Shrestha S, Gilani H, Gumma MK, Siddiqui BN, Jain AK. 2020. Dynamics and drivers of land use and land cover changes in Bangladesh. Reg Environ Chang. 20(2):54.

Yin J, Yin Z, Zhong H, Xu S, Hu X, Wang J, Wu J. 2011. Monitoring urban expansion and land use/land cover changes of Shanghai metropolitan area during the transitional economy (1979-2009) in China. Environ Monit Assess. 177(1-4):609–621.

Zhang B, Zhang Q, Feng C, Feng Q, Zhang S. 2017. Understanding land use and land cover dynamics from 1976 to 2014 in Yellow River Delta. Land. 6(1):20.

Zhang F, Tashpolat T, Kung H, Ding J. 2010. The change of land use/cover and characteristics of landscape pattern in arid areas An application in Jinghe, Xinjiang. Geo-Spatial Inf Sci. 13(3):174–185.

Zhang Y, Sun L. 2019. Spatial-temporal impacts of urban land use land cover on land surface temperature: Case studies of two Canadian urban areas. Int J Appl Earth Obs Geoinf. 75:171–181.