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Spatiotemporal Analysis of Urban Sprawl and Ecological Quality Study Case: Chiba Prefecture, Japan

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Abstract: The Japanese City Planning Act aims to control urban sprawl and promote compact urban development. Despite Japan's aging population, urban sprawl remains a concern in shrinking sprawl situations. This impacts ecosystem services owing to the loss of natural areas. Ecological quality is regarded as a basic parameter for preventing urban sprawl. This study examined urban sprawl, ecological quality, and their relationship in Chiba Prefecture within the spatial context of the metropolitan region. Utilizing Shannon entropy and landscape metrics for urban sprawling studies, the analysis revealed a gradual shift towards compact development at the center, while the urban periphery was unevenly distributed. The remote sensing ecological index (RSEI), supported by remote sensing, assesses ecological quality. Despite some limitations, the average RSEI indicated moderate quality, offering a suitable human environment. Pearson's calculations were used to determine the inverse correlation between urban sprawl and ecological quality. Chiba's slight increase in sprawl was attributed to the transition from non-compact to eco-city development. The proposed plans were formulated based on similar urban sprawl and RSEI patterns in other cities for further sustainable compact development.

Keywords: ecological quality; landscape metric; remote sensing; RSEI; Shannon entropy; urban sprawl

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1. Introduction

The Japanese City Planning Act divides areas into Urban Promotion Areas (UPAs) and Urban Control Areas (UCAs) [1]. UPAs encompass all presently developed zones, including expansive land to facilitate urban growth, whereas UCAs include protected areas and future development sites as safeguarding resources. The act aims to prevent uncontrolled expansion, manage growth, and maintain ecological balance, which is defined as preventing uncontrolled sprawl.

Several studies have used the term urban sprawl. However, Yoshida cited in Jaeger defined urban sprawl as the expansion of building or settlement areas into suburban and rural areas in the fringes [2]. This type of development eventually leads to the loss of natural areas and ecosystem services [3]. Japan's aging population and declining birth rates contribute to changes in urban demographics [4]. It is predicted that by 2050, there will be fewer children and more elderly individuals. With this situation, does the issue of land consumption and urban sprawl subside with the cessation of urban expansion? Klug and Hayashi explained that urban sprawl will continue to exist and is called "shrinkage sprawl", which is depicted by the expanded urban footprint accompanied by a density decline across the area, causing increased dispersion compared to growth sprawl [5]. Research conducted by Steven Fina and Siedentop in Germany explained that the shrinkage sprawl indicator is the aging population and migration balance, and shrinkage sprawl negatively impacts infrastructure efficiency, especially for vacant housing and underutilized supply networks [6]. Yokohari et al. supported this perspective, noting that Japan's typical urban sprawl has resulted in unmanaged buildings and vacant plots on the outskirts due to residential zones in the suburbs [7], losing their vigor and causing older adults to move to the city center [1]. These vacant buildings pose maintenance and management challenges. To mitigate any additional decrease in density caused by peri-/suburban development, city planning UPA and UCA systems should continue to be supported in Japan.

Globally, major metropolitan regions can benefit from the implementation of the City Planning Act's UPAs/UCAs in the Tokyo Metropolitan Area, which is considered to be a successful example of a developing city [8]. In this metropolitan area, there are areas outside the city planning area and non-UPA/UCA delineations, known as the UUA zone, where loose land use regulations allow for large-scale commercial development, including protected forests and agriculture. Without clear or specific regulations, this can lead to the depletion of natural resources and urban sprawl occurrence [9]. Mashima and Kawakami highlighted the significant number of development permits granted in metropolitan areas, highlighting the importance of monitoring the development levels of UPAs to prevent urban sprawl in UCAs [10]. Natural forests and agricultural areas fall under the UCA and UUA categories. This underscores the importance of analyzing UPAs/UCAs/UUAs for future planning in Japan.

Chiba Prefecture, with the largest UCA and UUA zones outside UPAs in the Tokyo Metropolitan Area, according to the National Land Survey 2020, offers a prime location for studying and assessing this situation. However, although Chiba Prefecture, as part of the Metropolitan Area, boasts a diverse natural environment, including Satoyama and Satoumi, reports from the Chiba government have revealed a gradual loss of these lands over the years. For instance, the forestry area decreased from 168,562 ha in 1990 to 155,292 ha in 2020, whereas the agricultural area decreased from 4448 ha in 2000 to 3853 ha in 2020 [10]. Although no specific reasons were mentioned, these transformations are believed to result from demographic factors.

Fundamentally, the natural landscape, including forests and agriculture, provides ecosystem service components such as biodiversity, soil conservation, water management, carbon storage, sociocultural value, climate change mitigation [11], food production, and land reclamation [12]. Understanding the existence of natural areas is important for restoring and enhancing ecosystem services and protection. The foundation of ecosystem services can be described as an ecological quality evaluation that measures the temporal and spatial operation of ecosystems for human living [13]. Urban sprawl typically results in the loss of natural landscapes, negatively influencing various ecosystem services [14]. Therefore, ecological quality evaluations can be regarded as a means of preventing urban sprawl.

Urban sprawl and fragmentation are closely related phenomena in which fragmented urban patches often coexist with non-urban uses [15,16]. In studies of landscape fragmentation, the Shannon entropy index and landscape metrics are commonly employed to quantify the level or degree of urban sprawl/extension. The Shannon entropy index enables decision makers to quantify urban sprawl towards the edge, making it useful for assessing sprawl at the prefecture level. Landscape metrics provide valuable insights into landscape structure and have low sensitivity to changes in spatial configuration across landscape patches [15], making them suitable for assessing sprawl at the city level.

Meanwhile, few assessments have analyzed the ecological quality of a region. The remote sensing ecological index (RSEI) introduces a novel concept for ecological assessment that utilizes remote sensing with multiple indicators and multi-year time series. In this study, the spatiotemporal analysis combined spatial and temporal correlations, providing advantages over traditional spatial analyses. It allows for the visualization of the geographic and temporal distribution of phenomena in epidemiological data, incorporating space–time information, especially when conducting assessments of urban areas such as Chiba Prefecture. Therefore, this study aimed to explore and characterize urban sprawl at the prefecture and city levels, to understand ecological quality, and to analyze the relationship between urban sprawl and ecological quality during the study period as a fundamental framework for future decision makers in urban planning in Chiba Prefecture.

2. Materials and Methods

2.1. Study Area

Chiba Prefecture within the Tokyo Metropolitan Region aims to create a sustainable and compact urban structure for future city planning. The population of 122,398,413 in 1990 was reduced to 122,031,000 in 2022 [17]. With a declining population, the prefecture recognizes the need to adapt to the needs of future residents. The City Planning Master Plan designates Urbanization Promotion Areas (UPAs) and Urbanization Control Areas (UCAs), although some areas are outside the delineation. Among the 53 cities in the Chiba Prefecture, 36 had designated areas (UPA/UCA/UUA delineated areas), 24 had delineated areas (UPAs/UCAs), and 14 had non-delineated areas (UUA non-delineated area) (Figure 1). Since the agriculture, forestry, and fishery industries in the prefecture face the challenges of declining productivity due to a shrinking workforce and an aging population, urban sprawl contraction and compact city creation are some of the target achievements.

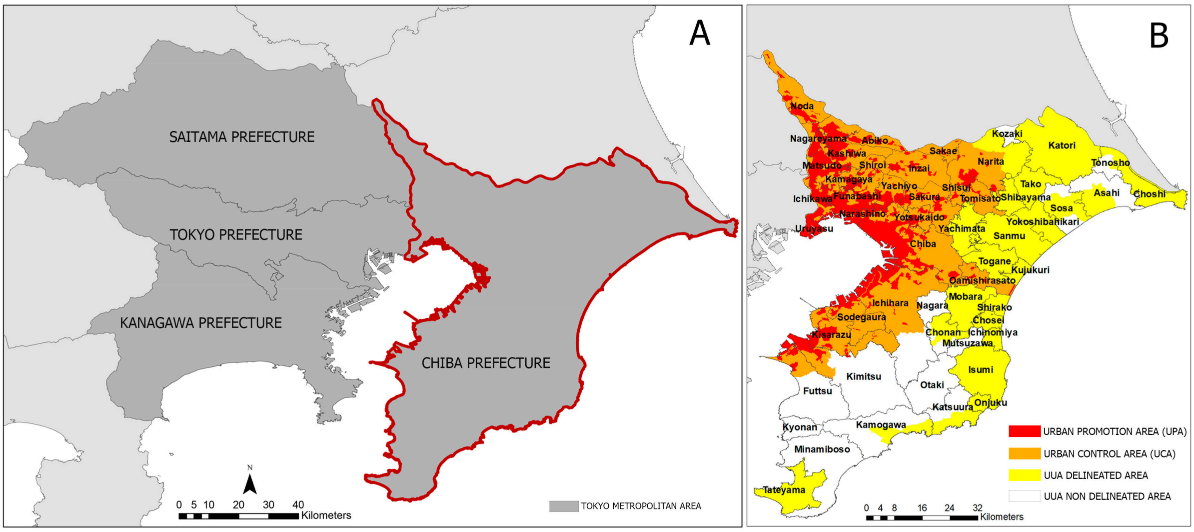


Figure 1. Study location: (**A**) Chiba Prefecture in Tokyo Metropolitan Area; (**B**) city planning of Chiba Prefecture.

2.2. Data Source

For this study, a spatial database was developed to model urban sprawl and the RSEI. The basic map acquired for the urban sprawl analysis was the Land Use Land Cover (LULC) map. The Prefecture Administrative and City Planning Delineation maps were freely downloaded from the National Land Numerical Information "URL https://nlftp.mlit.go.jp/ksj/ (accessed on 15 December 2022)" to support the analysis. The LULC and RSEI maps were obtained using the Google Earth Engine (GEE) platform. This tool operates on a web-based platform, enabling the comprehensive analysis and interpretation of diverse environmental studies [18]. To ensure the spatial results, Landsat data were used because of their high spectral resolution and because they provide long-term data records [19]. Specifically, Landsat-5 data from 1990 and Landsat-8 data from 2021 were employed to represent the past and present situation in the study area. Within the GEE platform, cloud detection and masking techniques were explored to accurately determine true surface reflectance values.

2.3. Research Methods

2.3.1. Land Use Land Cover (LULC) Assessment and Accuracy Assessment

LULC assessments were conducted using the Random Forest Algorithm (on the Google Earth Engine (GEE) platform, which is known for its robust and near-accurate performance in land cover classification) [20]. This study used sample data for each classification scenario for training. The sample data were categorized into three standard classes: built-up, vegetation, and water bodies. Built-up areas included residential, industrial, and commercial areas, as well as roads. Vegetation encompassed agricultural lands, grasslands, forests, and woodlands. Waterbodies represented open water, such as lakes, rivers, streams, and reservoirs [21–23].

The training data were used to classify the RF model into trees for prediction and classification. Approximately 910 points per class were randomly selected throughout the Tokyo Metropolitan Area, including Tokyo, Saitama, Kanagawa, and Chiba prefectures. The generated random forest classifier was executed using a GEE script. The classification was divided into training (70%) and validation (30%) samples for accuracy assessment. The accuracy assessment was performed using the Kappa coefficient, and a value above 0.8 was considered to be strong preliminary data for further analysis. The GEE platform facilitated filtering, classification, and accuracy assessment processes, utilizing functions such as ee.ImageCollection.filterBounds(), ee.ImageCollection.filterDate, ee.Classifier.smileRandomForest(), and ee.ConfusionMatrix.kappa(). The final classified images were exported to ArcGIS for further analysis.

2.3.2. Urban Sprawl

Prefecture Level

Regarding urban development in the Tokyo Metropolitan Area, urban growth results in outward expansion from Tokyo City to the surrounding regions [9]. Therefore, Shannon entropy was utilized to understand the distribution of urban sprawl phenomena from Tokyo to Chiba Prefecture at the metropolitan level. Shannon's entropy (Hn) was applied to assess the level of spatial distribution among zones where the Tokyo Station in Tokyo City precisely served as the center point for this analysis [9].

Using the LULC map downloaded from the GEE, the study area was divided into two classifications: urban (built-up) and non-urban (vegetation and water body), using ArcGIS Pro 2.18 software and the Iso-Cluster Unsupervised and Reclassify tools. The Shannon entropy formula measures the pattern of built-up areas (urban areas) using the observed values and probabilities within each zone [24]. The concentration zone was generated through buffer analysis from Tokyo Station at 5 km intervals and formed approximately 105 km within the prefecture. Urban sprawl in Chiba Prefecture was further divided into three zones: (1) the center, which covered approximately 50% of the urban area; (2) the fringe, with 30% of the urban area; and (3) the periphery. The formula for Shannon entropy was proposed as follows [25].

$$H_n = \sum_i^n p_i \text{Log}(1/p_1) \tag{1}$$

$$p_i = xi \sum_i^n x_i \tag{2}$$

$$H'_n = \sum_i^n p_i \text{Log}(1/p_1) \tag{3}$$

where Hn represents Shannon entropy, xi is the value for built-up areas in a particular zone, n denotes the number of zones, and Pi (probability or portion) is the ratio of built-up areas within zone i to the total built-up area in the region. The values of the Shannon entropy ranged from 0 to 1. A higher H′n value indicates a significant degree of dispersion with a low concentration of built-up areas or high sprawl, whereas a lower H′n value indicates less sprawl.

City Level

The Fragstat software (FRAGSTAT V4.2) is commonly used to analyze landscape structures, particularly fragmentation. In this study, class metrics for the urban type were used to analyze urban sprawl in Chiba Prefecture, focusing on the landscape structure of each city. Therefore, the overall landscape metrics were calculated for each of the 53 cities in the Chiba Prefecture.

From the pre-individual analysis in different sources, out of 44 available class metrics with 18 general class metrics that describe urban sprawl fragmentation, 8 metrics showed a positive correlation with the fragmentation value [26–38]. This implied that higher metric values indicated higher levels of fragmentation. Unlike previous studies, which considered all metrics simultaneously, this study focused on assessing the extent and level of sprawl in each city. To analyze urban sprawl distribution, the positive correlation of each metric was calculated, highlighting the significant value expressed by high fragmentation. Detailed information on the eight landscape metrics is presented in Table 1

Table 1. Landscape metric information.

No.	Metric	Class	Description
1	Total Edge (TE)	Area-Edge	Range: TE > 0, without limit
2	Perimeter–Area Fractal Dimension (PAFRAC)	Shape	Range $1 \leq$ PAFRAC ≤ 2
3	Mean Fractal Dimension Index (FRAC_MN)	Shape	Range $1 \leq$ FRAC_MN ≤ 2
4	Mean Shape Index (SHAPE_MN)	Shape	Range: SHAPE_MN > 0, without limit
5	Mean of Euclidean Nearest-Neighbor Distance (ENN_MN)	Aggregation	Range: ENN_MN > 0, without limit
6	Number of Patch (NP)	Aggregation	Range: NP > 0, without limit
7	Landscape Shape Index (LSI)	Aggregation	Range: LSI > 0, without limit
8	Landscape Division Index (DIVISION)	Aggregation	Range $0 \leq$ DIVISION ≤ 1

This study derived the concept of urban sprawl distribution using the overlay technique. The overlay involves stacking map layers, extracting information, and forming new layers. Composite maps can be created for visualization [39]. Typically, the overlay process uses raster images and a geographic information system (GIS). However, in this study, the eight selected landscape metrics were treated as value data layers, with 53 cities as features. Cumulative values were assessed and divided into three categories (low, moderate, and high) based on the frequency distribution using the maximum and minimum values from the cumulative data in 1990 and 2021 to ensure an equivalent range distribution.

2.3.3. Remote Sensing Ecological Index

The RSEI model is composed of four indicators: Vegetation Index (NDVI), Humidity Index (WET), Dryness Index (NDSI), and Heat Index (LST) [40]. The selected four indicators are related to human intervention and the ecological environment [41]. These indicators were calculated in the GEE platform using image expressions following the calculations in Table 2 and further analyzed using ArcGIS Pro. A water mask using the Modified Normalized Difference Water Index (MNDWI) was applied to exclude water interference, which leads to inaccuracies in calculating the humidity index [42]. To evaluate the RSEI, a principal component analysis (PCA) was performed for all four indicator images. Below is a gradual step in the PCA.

Table 2. RSEI indicator information.

No.	Indicator	Calculation Method	Explanation
1	NDVI	NDVI = (ρNIR − ρR)/(ρNIR + ρR)	ρB: Blue Band ρG: Green Band ρR: Red Band ρNIR: Near-Infrared Band ρSWIR1: Short-Wave Infrared 1 Band ρSWIR2: Short-Wave Infrared 2 Band IBI: Index Based Build-up SI: Soil Index Lλ: the radiance value (Landsat 5: 6 Band, Landsat8: 10 Band) Tb: the at-satellite brightness temperature K1 and K2: thermal conversion constants A: the wavelength of the thermal infrared band; ρ = 1.4380 × 10^4 µm; ε: surface-specific emissivity
2	WET	WET^{TM} = 0.0315ρB + 0.2021ρG + 0.3102ρR + 0.1594ρNIR − 0.6806ρSWIR1 − 0.6109ρSWIR2 WET^{OLI} = 0.1511ρB + 0.1972ρG + 0.3283ρR + 0.3407ρNIR − 0.7117ρSWIR1 − 0.4559ρSWIR2	
3	NDBSI	IBI = {2ρSWIR1/(ρSWIR1 + ρNIR) − [ρNIR/(ρR) + ρG/(ρG+ ρSWIR1)]}/{2ρ SWIR1/(ρ SWIR1 + ρNIR) + [ρ NIR/(ρNIR + ρR) + ρG/(ρG + ρSWIR1)]} SI = [(ρSWIR1 + ρR) − (ρB + ρNIR)]/[(ρSWIR1 + ρR) + (ρB + ρNIR)] NDBSI = (IBI + SI)/2	
4	LST	$LST = \frac{T_b}{\left[1+\left(\frac{\lambda T_b}{\rho}\right)\ln\varepsilon\right]}$	
5	MNDWI	MNDWI = (ρG − ρSWIR1)/(ρG − ρSWIR1)	

1. A comprehensive index was constructed using standardization to minimize the impact of varying numerical values of different indices on the outcome [43].

$$NI = (I - I_{min})/(I_{max} - I_{min})$$

2. Principal component analysis (PCA)

$$RSEI = f\{NDVI, Wet, NDSI, LST\}$$

3. These four indices were integrated to be 4-band images (principal components 1–4). According to the contribution of each component, if the total variance contribution of a specific component reaches or exceeds 85%, the component encapsulates the majority of the significant information [44].

$$RSEI = PCA1(NDVI, WET, NDSI, LST)$$

4. The RSEI values were presented as grades I–V (I: very good, II: good, III: moderate, IV: poor, V: very poor) [45]. Standardization was performed to simplify the evaluation.

2.3.4. Relationship between Urban Sprawl and RSEI

The Pearson correlation introduced by Karl Pearson was used to establish an essential correlation [46]. It measures the relationship between two variables ranging between −1 and +1, and 1 indicates a perfect correlation. The study included a sample size of 53 cities in Chiba Prefecture, where the mean RSEI and urban sprawl values were analyzed. The Pearson correlation assumes representative data variables with a ratio scale [47], and because both variables in this study met these criteria, a Pearson analysis was employed for the correlation assessment.

3. Results

3.1. Land Use Land Cover (LULC) Assessment and Accuracy Assessment

The accuracy assessment showed that the Kappa Accuracy for the LULC Map in 1990 and 2021 was above 0.8, indicating that the map was acceptable and appropriately used for further analysis. According to the LULC assessment in Table 3, Chiba Prefecture exhibited the highest vegetation coverage throughout the study period, indicating significant greenery in the region following Chiba, Saitama, Kanagawa, and Tokyo. However, the assessment indicated that built-up areas expanded continuously across all prefectures during the entire study period. This implies that urban development and construction activities have occurred over the past 31 years in the Tokyo Metropolitan Area (Figure 2).

Furthermore, the assessment revealed that the presence of water bodies in Chiba has exhibited a declining trend. Overall, in Chiba, our focus study area, the increase of 51,318.58 ha in urban coverage represents approximately half of the total changes observed during the study period.

Table 3. LULC classification in Tokyo Metropolitan Area 1990–2021.

LULC		Chiba (ha)	Tokyo (ha)	Kanagawa (ha)	Saitama (ha)
Vegetation	1990	419,857.48	94,118.93	166,492.63	296,088.10
	2021	382,455.96	7630.11	140,126.16	223,069.90
	Changes	−37,401.52	−17,588.82	−26,366.47	−73,018.20
Waterbody	1990	38,736.20	16,057.60	14,652.73	15,091.50
	2021	28,701.28	7515.88	9870.86	15,712.16
	Changes	−10,034.93	−8541.72	−4781.87	+620.66
Built-up	1990	56,200.74	68,398.19	60,365.89	68,543.52
	2021	103,642.22	94,526.09	91,517.74	140,939.93
	Changes	+47,441.48	+26,127.91	+31,151.85	+72,396.41
Kappa Accuracy	1990	0.81			
	2021	0.83			

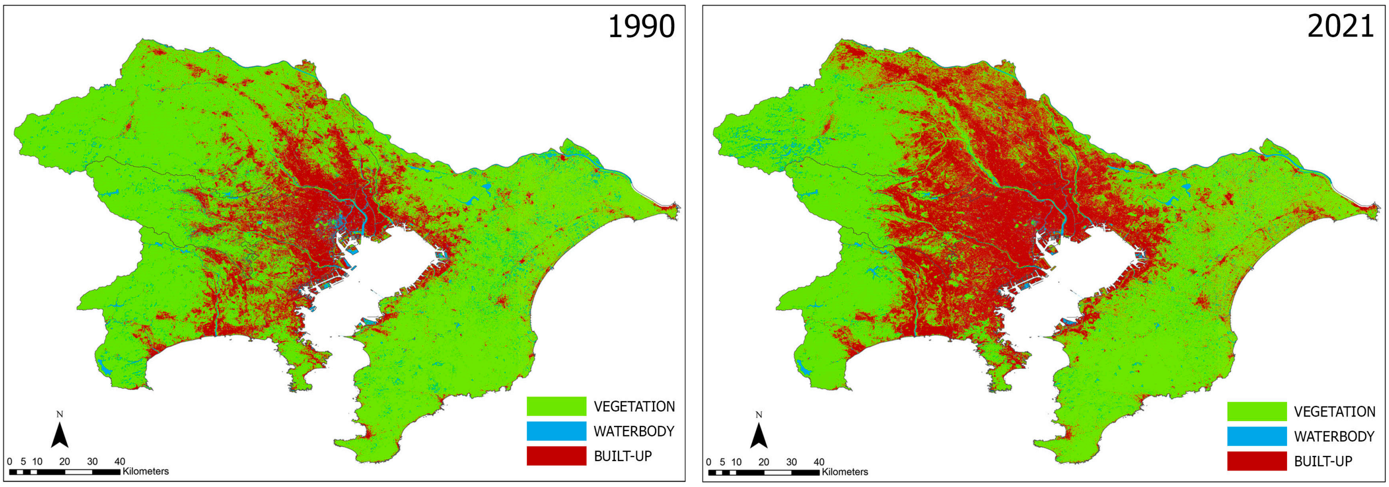


Figure 2. Land use in Tokyo Metropolitan Area in 1990 and 2021.

To examine the consumption in built-up areas in Chiba Prefecture, the LULC was divided into urban and non-urban areas. According to the City Planning Chiba Prefecture, detailed in Figure 3, the highest urban expansion in the UPAs was found in Chiba City. Furthermore, Narita had the highest urban growth value in the UCAs zone in 2021. For the UUA delineated, Choshi in the northeastern part of Chiba showed a sharp increase in urban value during 1990–2021. Asahi, which is located alongside Narashino, is partially categorized as UUA non-delineated, and the rest is UUA outside city planning, which illustrates its highest urban growth. Cities located along the coastline, such as Chiba, Choshi, and Narashino, experienced significant urban growth compared with other cities. Narita City, situated on the border of Chiba and Ibaraki prefectures, has experienced urban development. Therefore, although UPAs serve as the designated urban cover and base urban area, the findings of this study indicate that UCAs and UUAs, which should ideally be restricted from urban development, exhibited continuous urban expansion up to 2021.

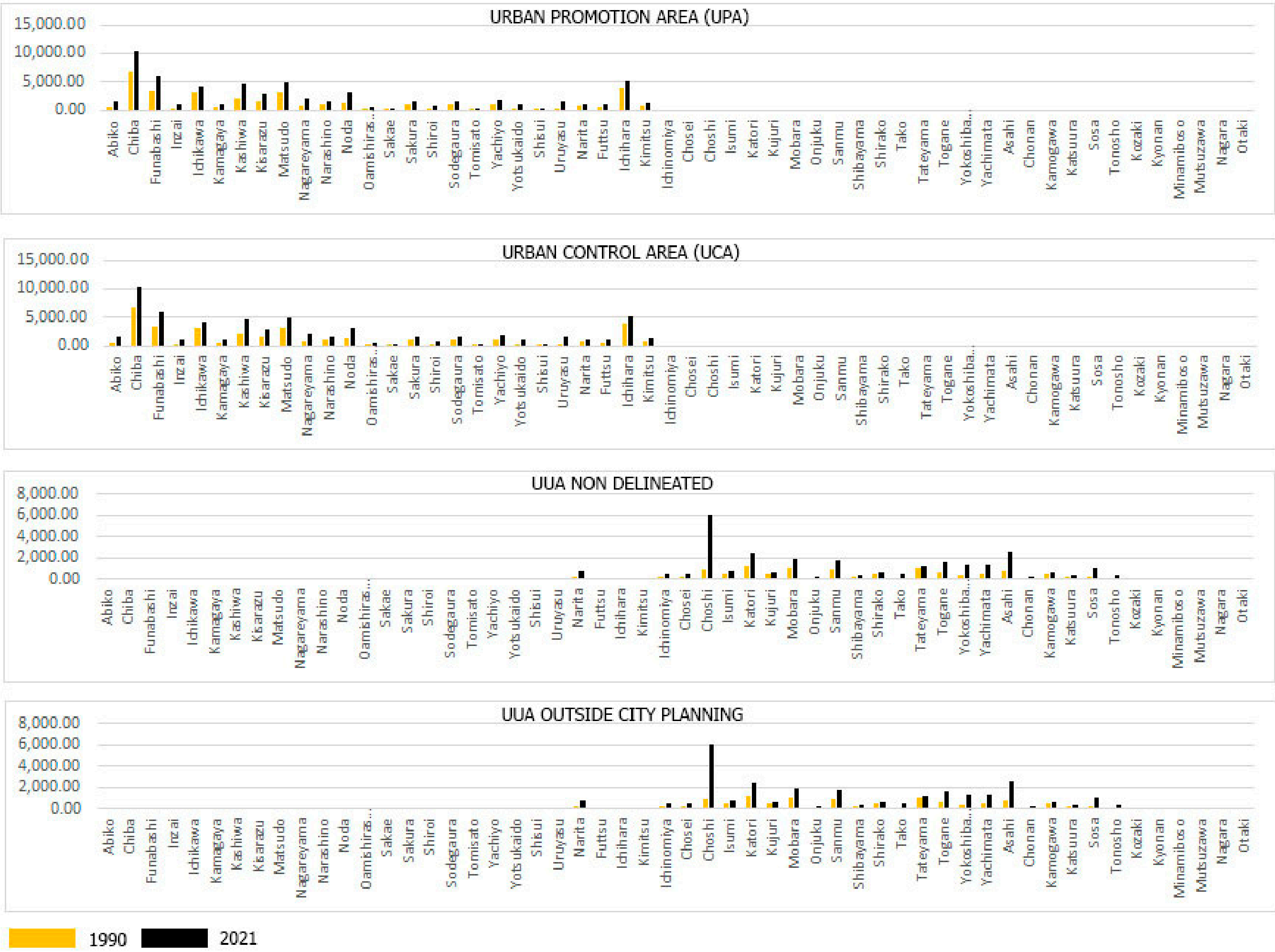
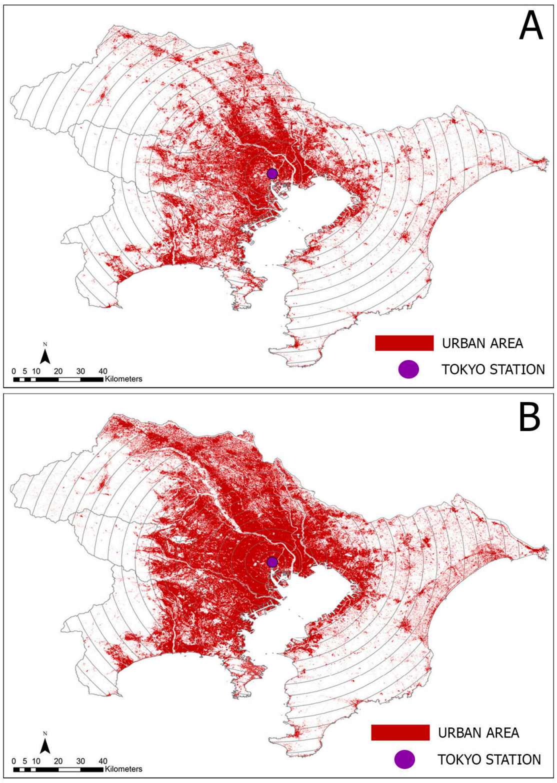


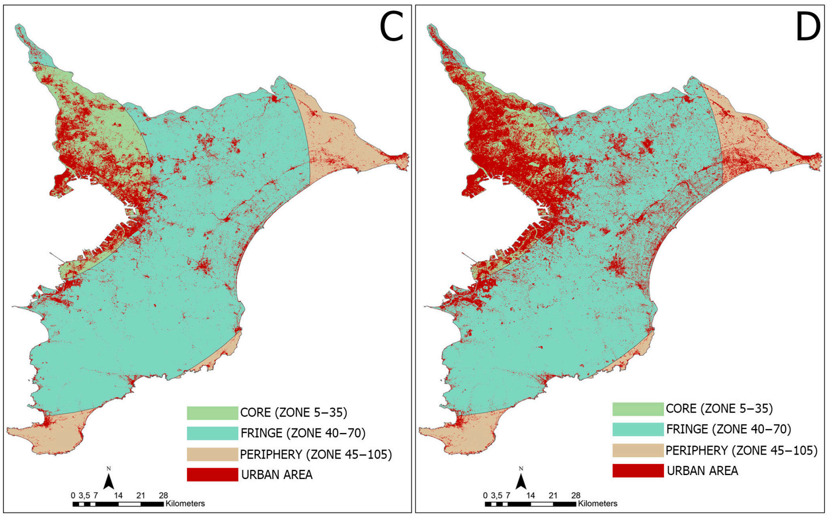
Figure 3. The urban existence and trend in UPAs, UCAs, and UUAs 1990–2021.

3.2. Urban Sprawl Analysis in Chiba Prefecture (Prefecture and City Level)

Research conducted in Chiba Prefecture revealed a higher entropy value than that in other prefectures, with a slight increase in 2021 (0.558 in 1990 and 0.560 in 2021). Tokyo Prefecture had the lowest Shannon entropy value in 1990, but it continued to increase and reached its highest growth towards 2021. This increasing value of Shannon entropy is considered to be the beginning of the urban sprawl phenomenon. Kanagawa Prefecture was the only prefecture observed to show a negative Shannon entropy trend. This indicates a gradual absence of urban sprawl in this region. However, for Chiba Prefecture, an urban sprawl phenomenon exists in this area, which is higher than that in other prefectures, indicating that urban cover exists in the fringe or periphery far from the Tokyo Metropolitan Area as a city center.

Urban sprawl in Chiba is divided into three zones: the center, fringe, and periphery. From the calculations for 1990 and 2021, the core interval was extended to zone 35 (35 km), the urban fringe was 70 km, and the periphery was the remainder, up to 105 km. Figure 4 shows that the values in the three zones almost entirely reached the midpoint of 0.5. The fringe area, which predominantly covers the total area of Chiba Prefecture, recorded the highest Shannon entropy value, showing further urban footprint dispersion compared to other zones. Meanwhile, the lowest Shannon value, which is integrated with the core, is located close to Tokyo's urban center, indicating that the urban area was constructed towards compact development. Generally, the trend development of Shannon entropy in each zone expresses the declining value of the core and fringe, explaining why urban areas are becoming closer and more centralized. In contrast, the periphery increased in 2021, revealing the uneven progress of urban distribution toward the edge.





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	Chiba	Tokyo	Kanagawa	Saitama
1990	0.558	0.442	0.513	0.528
2021	0.560	0.457	0.502	0.553
Trend	+ 0.002	+ 0.035	− 0.11	+ 0.025

F

	Core	Fringe	Periphery
1990	0.428	0.565	0.437
2021	0.418	0.521	0.488
Trend	− 0.01	−0.044	+ 0.051

Figure 4. Urban area in TMA in (**A**) 1990 and (**B**) 2021, urban area in the core, fringe, and periphery in the Chiba Prefecture in (**C**) 1990 and (**D**) 2021, (**E**) Shannon entropy value and trend in each prefecture at TMA, (**F**) Shannon entropy value and trend in the core, fringe, and periphery in the Chiba Prefecture.

Furthermore, city-level sprawl categorized cities into low, moderate, and high sprawl based on eight landscape metric assessments. From the analysis of the table in Figure 5, several observations were made regarding the urban characteristics and development patterns of different municipalities over time. (1) Narashino had the highest TE value in 1990, indicating a more fragmented landscape compared to other cities. However, the northern part of Abiko's urban area was more fragmented by 2021. (2) Shirako had the highest NP value in 1990, but this was then adopted its surrounding area, Chosei, in 2021. This suggests that the quantity and distribution of urban patches around Chosei and Shirako have become more scattered over the years. (3) The increase in LSI values for Narashino and Uruyasu in 1990, as well as Kujuri and Uruyasu in 2021, indicated that the urban areas in these locations have become more disaggregated, or the length of edges within the landscape has increased. This suggests a trend toward a more fragmented urban landscape. (4) Uruyasu and Narashino for SHAPE_MN showed more elongated shapes in both 1990 and 2021, indicating that the urban areas were spatially far apart. (5) FRAC_MN, PAFRAC, and Division: Uruyasu and Narashino exhibited high and increasing values for these metrics, indicating that the urban areas in these municipalities had higher shape complexities and fragmentation degrees across the landscape over time. (6) Kozaki and Uruyasu had high ENN_MN values in 2021, indicating greater isolation and dispersion of urban patches. The areas with high ENN_MN values are located near the city center, Tokyo area, and coastal area, suggesting a dispersed and fragmented pattern of urban sprawl. Overall, the analysis suggests that urban development in these areas has shown signs of urban sprawl with increasing fragmentation, shape complexity, and dispersion of urban patches over time.

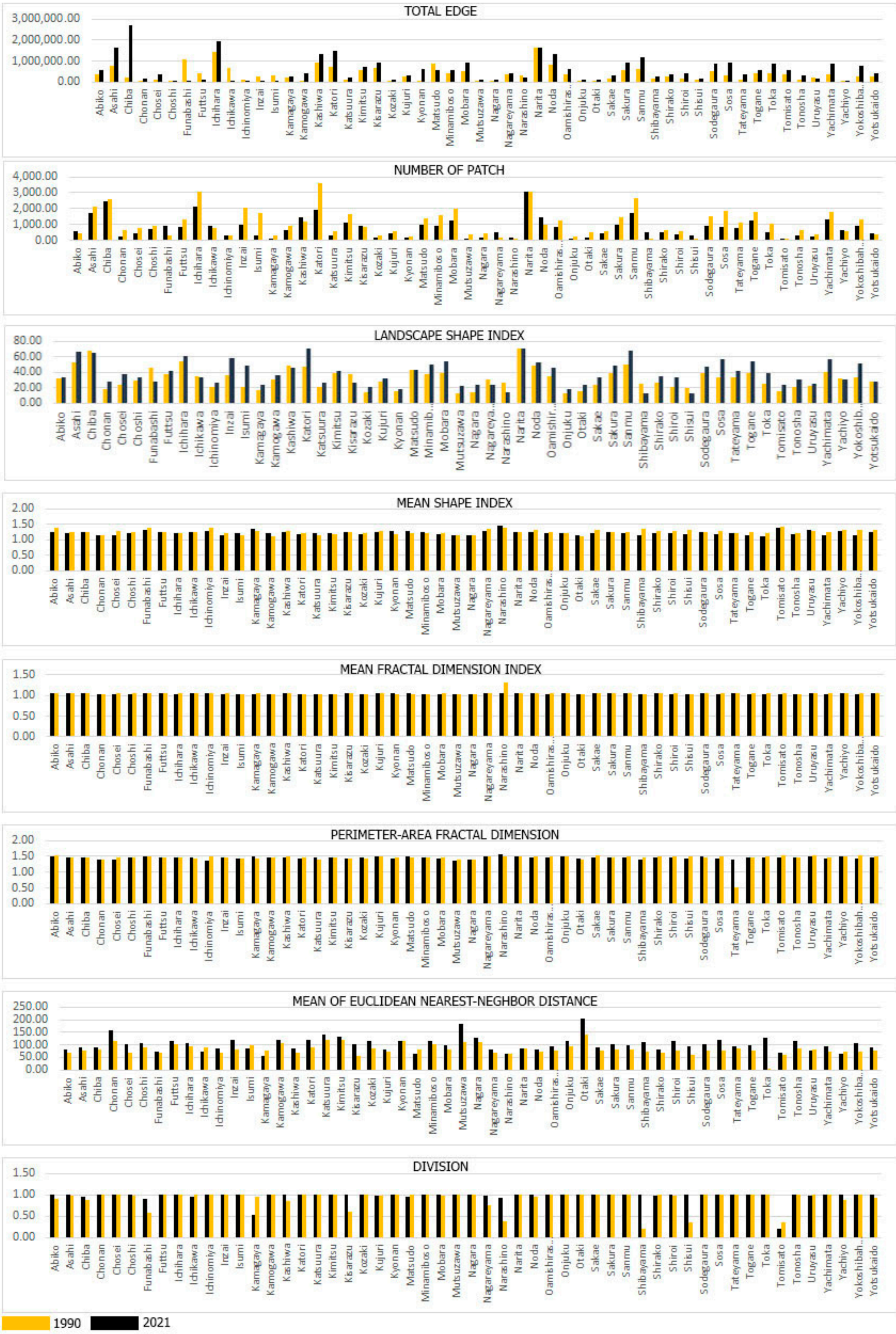

Figure 5. Landscape metrics trend in each municipality of Chiba Prefecture 1990–2021.

After applying the overlay technique to the eight landscape metrics in each city, as shown in Figure 6, the results indicated that in 1990, urban sprawl was the highest near the Tokyo area, indicating the influence of city development in Tokyo as the central hub. Some cities in northern Chiba exhibited moderate sprawl, whereas the southern region remained largely untouched by urban development because of its forested and mountainous areas. By 2021, high and moderate urban sprawl dominated the northern part of Chiba Prefecture, particularly in the coastline area and near the central metropolitan region. The southern region also experienced moderate to high sprawl. Over the period 1990–2021, urban sprawl was evident in several municipalities, with some cities experiencing a decline in sprawl owing to rapid development and urban compact formation near the Tokyo area. Conversely, Kyonan, located on the periphery, had the highest sprawl growth in 2021. Overall, most urban sprawl growth was observed in the fringe areas.

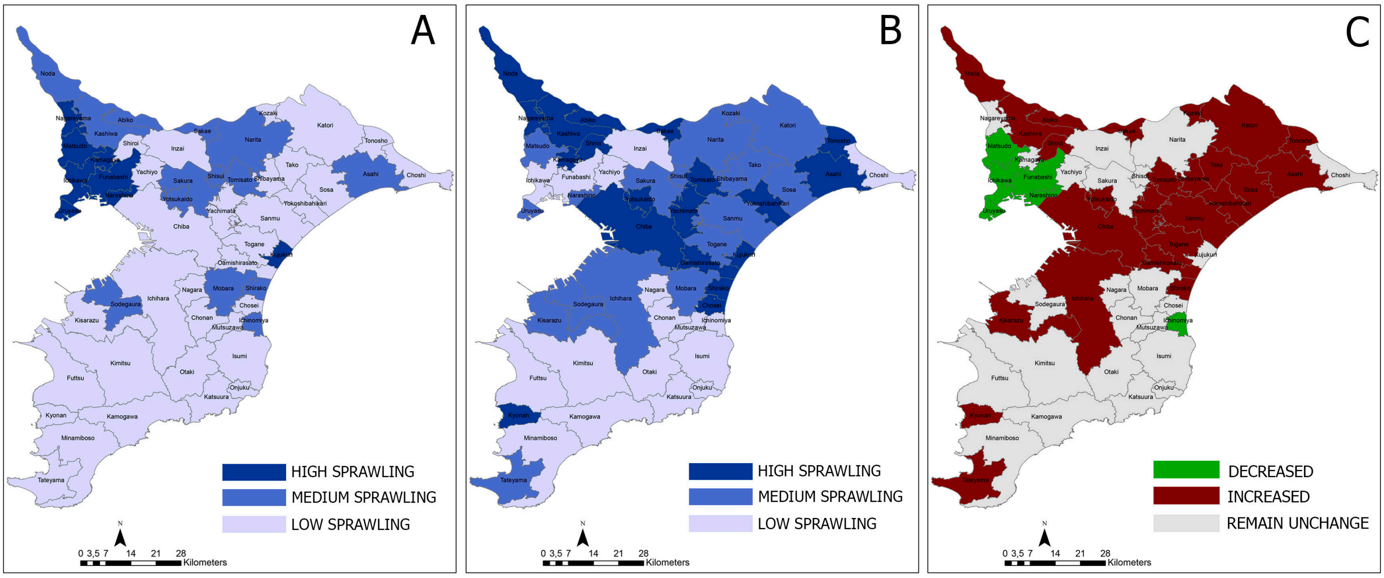

Figure 6. Urban sprawl degree in Chiba Prefecture in (**A**) 1990 and (**B**) 2021 (**C**) urban sprawl trend from 1990 to 2021.

Two perspectives were derived to explain urban sprawl in Chiba Prefecture, as depicted in Table 4.

Table 4. Urban sprawl classification based on prefecture and city level.

	Metropolitan Level: Shannon Entropy		City Level: Landscape Metric	
	1990	2021	1990	2021
Highest sprawling	Fringe	Fringe	Core and Fringe	Core, Fringe, Periphery
The highest urban sprawl growth	Periphery		Fringe	
The highest urban sprawl loss	Fringe		Core	

From the perspective of Tokyo's development, urban sprawl is concentrated in the fringe area, with a higher value compared with other zones. Sprawl tended to decrease but remained significant by 2021. Additionally, the peripheral area showed growth in urban sprawl. From an urban structural perspective, the core and fringe areas are crucial for urban sprawl. While some cities in the core are moving towards a compact structure, the surrounding areas continue to be affected by sprawl. Furthermore, the periphery is experiencing urban sprawl. Therefore, the urban fringe and periphery are key areas of concern for sprawl conditions.

3.3. RSEI Quality in Chiba Prefecture

Based on Table 5, PCA1 had a cumulative variance contribution rate exceeding 85% in 1990 and 2021, indicating that it represented most of the relevant variables. In PC1, NDVI and WET had positive values, while LST and NDSI were negative, implying that the increased values of surface temperature and anthropogenic floor reduces the RSEI quality, while vegetation cover and moisture can improve the ecological quality in Chiba Prefecture. The NDVI had the highest contribution value in 1990, indicating its strong influence on ecological evaluation, whereas the NDBSI value dominated in 2021. WET showed the lowest contribution, indicating a less significant effect on ecological quality. Additionally, the sum of the eigenvalues for LST and NDSI surpassed the total value of the eigenvalues of NDVI and WET, indicating weaker ecological enhancement from vegetation and humidity relative to the adverse influence of dryness and heat [48].

Table 5. Contribution component of PC1 for RSEI and average value for 4 indicators.

Indicator	Contribution Component (PC1)		Average Value	
	1990	2021	1990	2021
LST	−0.12906	−0.30183	0.43	0.38
WET	0.04945	0.14231	0.90	0.81
NDVI	0.73616	0.48384	0.62	0.77
NDBSI	−0.66255	−0.80904	0.48	0.46
Eigenvalue	0.01624	0.01466	1990	2021
Eigenvalue contribution Rate (%)	92.3725	85.8561		

The WET indicator had the highest average values in 1990 and 2021, whereas LST consistently had the lowest average value. In 2021, NDVI produced a positive value together with WET and supported the contribution of WET, leading to a high RSEI value. However, although the RSEI value increased, the expansion was not significant because of the existence and contribution of the NDBSI value. Therefore, observing the vegetation cover (NDVI) and dryness index (NDBSI) is important for assessing the ecological conditions of Chiba Prefecture.

The RSEI assessment in Chiba Prefecture showed an increase in average quality from 1990 to 2021 (0.551 in 1990 and 0.582 in 2021), indicating that the vegetation density was at a moderate level, while biodiversity factors were on average good, leading to a suitable living for settlement. However, certain constraining conditions make it unsuitable for long-term living [49]. The quality ranged from very poor to very good, with moderate quality covering a significant portion of Chiba. There was a decrease in very poor- (−141.060 ha) and poor-quality areas (−34,481.390 ha), indicating improvements in vegetation coverage and biodiversity. However, the declining value of good quality (−13,780.498 ha) suggested a loss of vegetation coverage and degradation in certain parts of Chiba. From Figure 7, urban centers showed moderate- and poor-quality concentrations near Tokyo and the coastal regions, while untouched areas, such as mountainous forests and agricultural fields, exhibited good and very good quality.

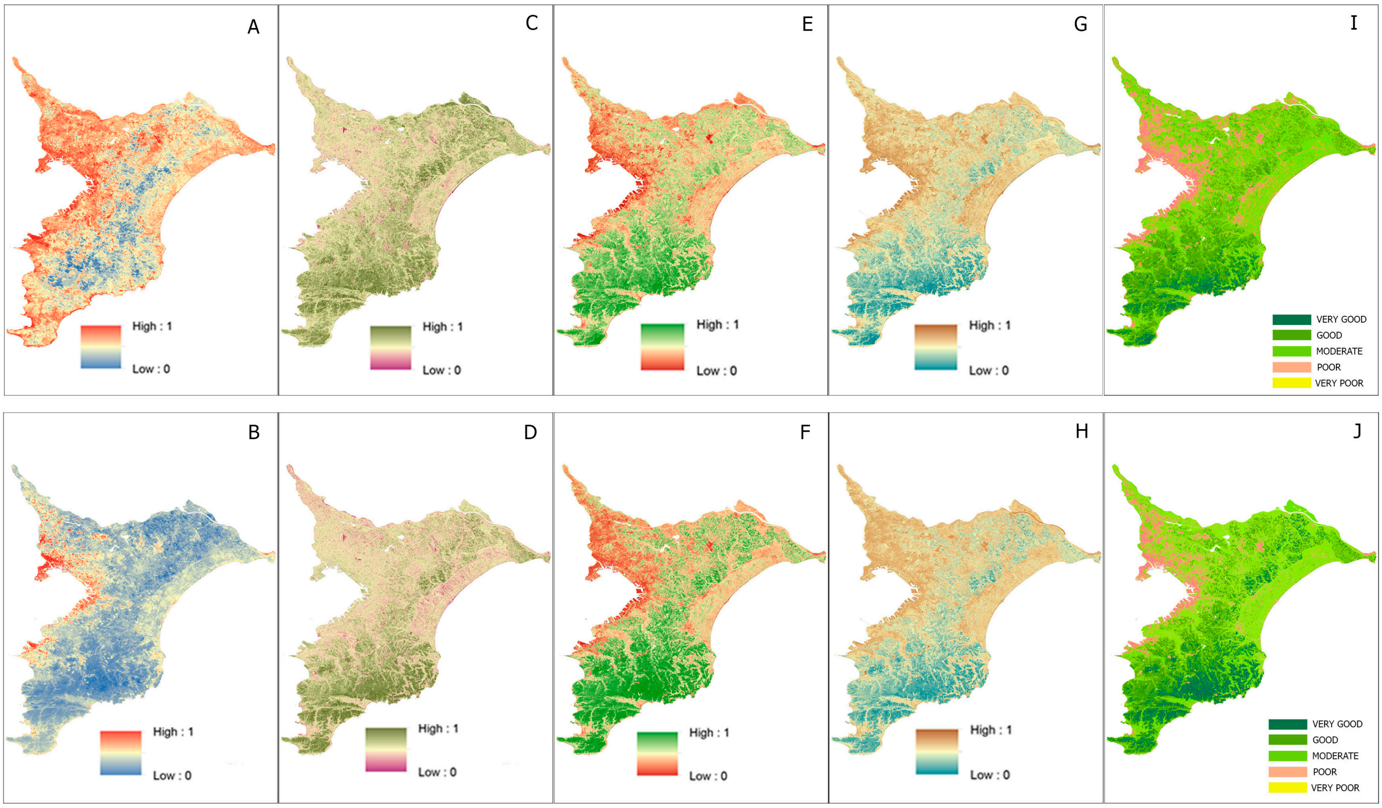

Figure 7. LST in (**A**) 1990 and (**B**) 2021, WET in (**C**) 1990 and (**D**) 2021, NDVI in (**E**) 1990 and (**F**) 2021, NDBSI in (**G**) 1990 and (**H**) 2021, RSEI in (**I**) 1990 and (**J**) 2021.

Figure 8 and Table 6 provide a detailed view of the spatiotemporal changes in the RSEI in Chiba Prefecture. The dominant trend exhibited no ecological change, followed by areas with improved ecological quality and degradation. Although the average RSEI increased in 2021, the overall trends suggested that the improvements were not statistically significant, as many locations maintained the same ecological quality as in 1990. Nevertheless, when comparing the improvement trend with the degradation trend, it becomes apparent that the ecological quality in Chiba Prefecture has shown signs of improvement for 21 years.

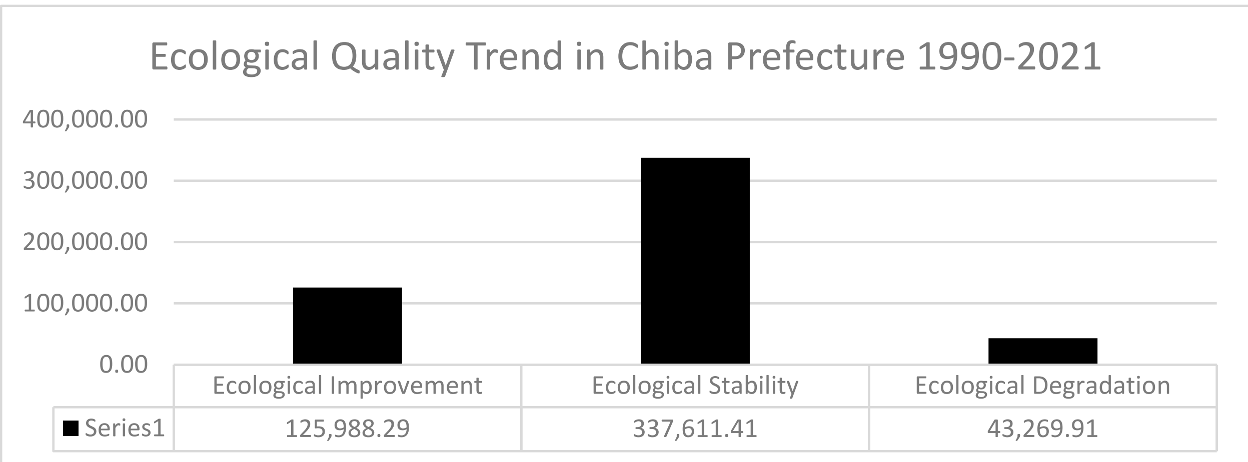

Figure 8. RSEI trend in Chiba Prefecture from 1990 to 2021.

Table 6. Total area for ecological quality from 1990 to 2021.

Quality Level	1990		2021		The Trend during 1990–2021 (ha)
	Area (ha)	Proportion (%)	Area (ha)	Proportion (%)	
Very Poor (0–0.2)	160.037	0.031	18.976	0.004	−141.060
Poor (0.2–0.4)	86,093.173	16.881	51,611.783	10.170	−34,481.390
Moderate (0.4–0.6)	236,116.137	46.296	250,599.317	49.373	14,443.180
Good (0.6–0.8)	155,928.230	30.573	142,147.733	28.010	−13,780.498
Very Good (0.8–1)	31,714.784	6.218	63,144.150	12.443	31,429.366
Mean	0.551		0.582		0.582

From 1990 to 2021, the ecological quality in Chiba Prefecture showed mixed changes. Five cities, Kamagaya, Nagareyamama, Noda, Tateyama, and Toka, experienced a decline in RSEI quality. Tateyama showed the highest degradation trend from good to moderate quality in 2021. These cities are near Tokyo or Narita, indicating vegetation loss and moisture degradation owing to urban development and terrestrial warming. In contrast, the ecological quality of cities surrounding Chiba, such as Ichikawa and Narashino, improved from poor to moderate. Based on Table 7, the improvement in the quality level showed that only Ichikawa and Narashino experienced a change in quality level, denoting an upgrade from poor to moderate. Therefore, even though most cities in Chiba are progressively developing, further municipalities may experience multiple negative changes. Furthermore, as shown in Figure 9 the mean RSEI quality ranged from poor to good, indicating that the area near Tokyo had a very poor ecological quality level. In contrast, the southern part of Chiba, specifically the Boso Peninsula, exhibited good ecological quality in 1990 and 2021, which should be protected for the future.

Table 7. Average RSEI value in each municipality in Chiba Prefecture from 1990 to 2021.

City	RSEI1990	RSEI 2021	Trend	City	RSEI 1990	RSEI 2021	Trend
Abiko	0.45	0.47	0.02	Nagara	0.60	0.65	0.06
Asahi	0.51	0.52	0.01	Nagareyama	0.47	0.44	−0.01
Chiba	0.46	0.50	0.04	Narashino	0.37	0.42	0.05
Chonan	0.64	0.66	0.04	Narita	0.49	0.54	0.05
Chosei	0.47	0.50	0.03	Noda	0.48	0.47	0.00
Choshi	0.55	0.57	0.02	Oamishirasato	0.48	0.53	0.04
Funabashi	0.41	0.43	0.02	Onjuku	0.67	0.69	0.02
Futtsu	0.64	0.66	0.02	Otaki	0.71	0.75	0.04
Ichihara	0.55	0.59	0.04	Sakae	0.45	0.50	0.05
Ichikawa	0.37	0.40	0.02	Sakura	0.50	0.54	0.04
Ichinomiya	0.55	0.57	0.02	Sanmu	0.54	0.58	0.04
Inzai	0.49	0.53	0.03	Shibayama	0.53	0.58	0.05
Isumi	0.63	0.66	0.03	Shirako	0.45	0.49	0.04
Kamagaya	0.46	0.45	−0.01	Shiroi	0.50	0.51	0.01
Kamogawa	0.71	0.74	0.03	Shisui	0.50	0.54	0.05
Kashiwa	0.45	0.46	0.01	Sodegaura	0.50	0.54	0.05
Katori	0.52	0.57	0.05	Sosa	0.53	0.54	0.01
Katsuura	0.72	0.73	0.02	Tateyama	0.64	0.54	−0.10
Kimitsu	0.65	0.68	0.03	Togane	0.50	0.54	0.04
Kisarazu	0.55	0.56	0.01	Toka	0.56	0.54	−0.01
Kozaki	0.50	0.55	0.15	Tomisato	0.48	0.53	0.05
Kujuri	0.44	0.48	0.04	Tonosha	0.54	0.56	0.02
Kyonan	0.68	0.71	0.02	Uruyasu	0.34	0.38	0.04
Matsudo	0.39	0.41	0.02	Yashima	0.50	0.52	0.03
Minamiboso	0.70	0.72	0.01	Yachiyo	0.47	0.48	0.01
Mobara	0.50	0.55	0.05	Yokoshibahikari	0.49	0.53	0.03
Mutsuzawawa	0.60	0.64	0.04	Yotsukaido	0.48	0.50	0.02

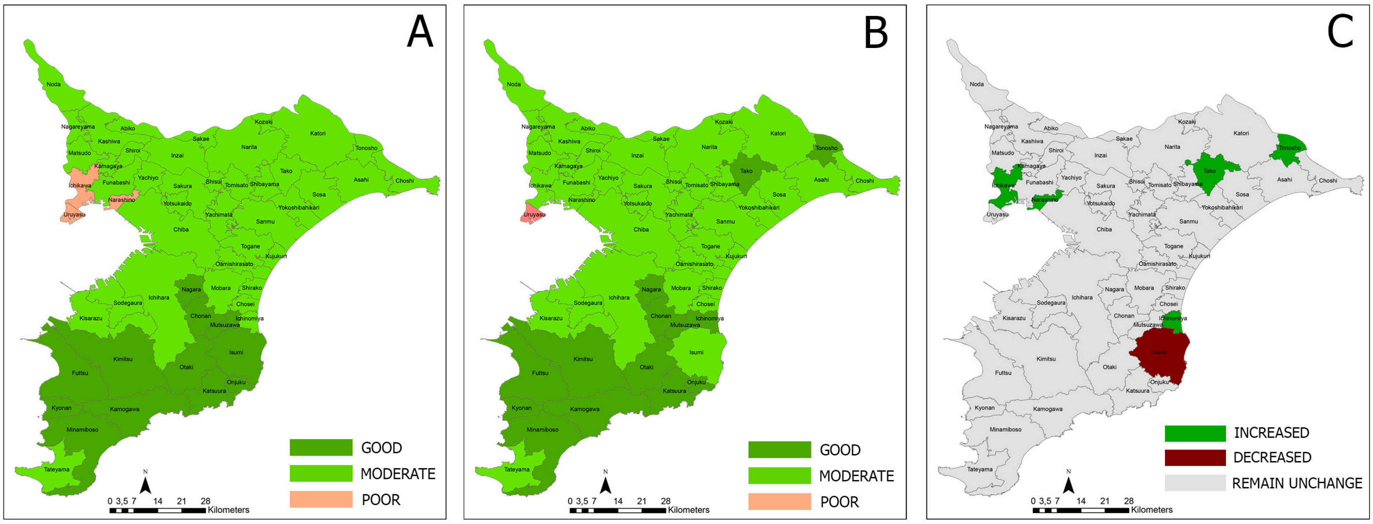

Figure 9. RSEI degree in Chiba Prefecture in (**A**) 1990 and (**B**) 2021; urban sprawl trend from 1990 to 2021 (**C**).

3.4. Urban Sprawl Analysis in Chiba Prefecture (Prefecture and City Level)

According to Table 8, urban sprawl and ecological quality were correlated, with urban sprawl negatively affecting ecological quality (RSEI). This is called inverse correlation. The correlation analysis revealed a strong negative relationship between urban sprawl and the RSEI, indicating that as urban sprawl increased, the RSEI decreased. The correlation values between the two variables decreased in 2021, suggesting a potential future decrease in urban sprawl and the RSEI. Compact landscape development is necessary for sustainable cities and for enhancing ecological quality.

Table 8. Pearson correlation between urban sprawl and RSEI in 1990 and 2021.

	Year 1990	
Pearson Correlation	**Urban Sprawl**	**RSEI**
Urban Sprawl	1	−0.786 **
RSEI	RSEI	RSEI
	Year 2021	
Urban Sprawl	1	−0.495 **
RSEI		1

** Correlation is significant at the level 0.01 level.

4. Discussion

4.1. Urban Sprawl from Prefecture and City Level

Historically, the metropolitan fringe area is a transition of nature that becomes progressively more agrarian in orientation, which is closer to the urban center; however, agricultural land use will eventually be given away to urban-oriented activities (rural–urban fringe). Toshio explained that the Tokyo Metropolitan Area divides the fringe area into inner and outer parts [50]. The inner region has experienced significant use and sharp decline since Japan's period of rapid economic growth. Meanwhile, the outer fringe is a portrayed region where, despite rural land dominance, the urban-oriented region is characterized by farming activities and extensive agricultural development. Some of the fringe areas, especially near the coast in Chiba Prefecture, are viewed as originating from urban areas that were primarily built in the early 1970s period and continue to develop where agrarian landscapes are mixed with settlement areas.

Follmann revealed that the urban periphery constitutes a wide range of geographical territories with the most dynamic place that presents urbanization because of the existence of built-up areas (built-up density) [51]. Therefore, fragmented structures threaten natural resources that have an environmental impact. However, what happens to the urban periphery when growth is very strong in the center? Does this affect the fringe area? The urban characteristics of Chiba Prefecture on the periphery were slightly untouched by the surplus in the urban core of Tokyo. The existence of the periphery towards the coastline results in its development. Although the center of Tokyo, which is near the core, is the main door for urban growth, it also begins at the edge of the coastal area. Notably, the total population in the fringe and periphery areas decreased from 3,143,973 in 1990 to 3,100,391 in 2020, with further projected decreases in subsequent years. In core areas where compact development was implemented, the total population increased from 2,653,809 to 3,090,513 [17]. As Chiba Prefecture experiences an aging population and sprawl, it has become crucial to focus on creating a compact development that concentrates the population on the fringe and periphery without disturbing the initially protected vegetation areas.

4.2. Good Ecological Quality in Chiba Prefecture

Good ecological quality during the study area was found in the northern part of Chiba as part of the Boso Peninsula. The Boso Peninsula is composed of the Kazusa, Mineoka, Miura, and Hota Groups and creates a hill and mountain range with a tectonic basin, rocky reefs, and various beach settings [33,52]. Therefore, the character landscape comprised natural parks, quasi-national parks, and fertile farmlands with relatively warm climates. Matsuyama et al. and Yoshiyo et al. explained that the vegetation cover concentrated around this region is dominated by broad-leaved evergreen forests and coniferous plantations, along with agricultural fields [53,54]. This vegetation cover is a sanctuary to rare and precious plant and animal life and large food sources, making it a natural treasure trove typical of the Boso Peninsula.

Good ecological quality is important in ecosystem services, especially in the forests and agricultural parts of Chiba Prefecture. According to the City Planning Act in Chiba, good-quality areas are mainly delineated as UUAs, with limited urban development. Medium-level quality was defined in the UPA and UCA regions, where the entire urban area was not supported. Considering the quality of the RSEI in 1990 and 2021, this indicates that the city's development is still aimed at achieving good results in accordance with city planning. However, even if the ecological value increases, the current city planning qualification should be continuously implemented to limit any negative changes in the future, especially in UCA and UUA delineations that are vulnerable to scattered building construction. In Chiba Prefecture, regulations for the protection of natural landscapes for protected forests, forest production, and privately owned forests were formed by the Forest Act and the Chiba Prefectural Ordinance concerning the optimization of forest land development activities. However, protecting and maintaining a good ecological quality area is important.

4.3. Planning Proposal Recommendation

Planning proposals can be developed for cities with similar characteristics based on the analysis of urban sprawl and RSEI quality levels.

Green infrastructure will play a crucial role in the development of low-density areas in terms of ecological enhancement, as shown in proposals 1–6 in Table 9 and Figure 10. Green infrastructure aims to create a balanced landscape incorporating social, environmental, and technological functions to achieve sustainability. This approach aligns with the aspiration of certain individuals to reside in an area or location with natural resources and a healthy lifestyle [55]. Green infrastructure, such as green walls, wetland roofs, and courtyards, including vegetation along streets, roadsides, and parks with stormwater management systems, creates green corridors and natural habitats [56–58], especially with native plant preservation [59]. Vertical allocation could be proposed to improve urban compactness, in which some floors are designated for work and the remaining floors for residential or other land use [60]. Furthermore, the eco-city program provides a compact landscape and can generally increase the ecological value. The framework of an eco-city is described as complete, sustainable, regenerative, improved environment, nurtured, highly organized, restoring nature's economy, and providing for all [61]. Furthermore, forest management should accumulate to achieve both forest growth and appropriate forest management. This model can serve as a valuable reference for these cities as they plan for a sustainable future.

Table 9. The correlated city with similar urban sprawl and RSEI level situation.

Proposal	City	Urban Sprawl	RSEI
1	Abiko, Asahi, Chiba, Chosei, Kamagaya, Kashiwa, Kujuri, Nagareyama, Noda, Oamishirasato, Sakae, Shirako, Shiroi, Tomisato, Yachimata, Yokoshibahikari, Yotsukaido	High sprawl	Moderate quality
2	Kyonan	High sprawl	Good quality
3	Uruyasu Ichikawa	Moderate sprawl Low sprawl	Bad quality Moderate quality
4	Ichihara, Katori, Kisarazu, Kozaki, Matsudo, Mobara, Narashino, Narita, Sakura, Sanmu, Shibayama, Shisui, Sodegaura, Sosa, Tateyama, Togane, Toka, Tonosha	Moderate sprawl	Moderate quality
5	Choshi, Funabashi, Ichinomiya, Inzai, Yachiyo	Low sprawl	Moderate quality
6	Chonan, Futtsu, Isumi, Kamogawa, Katsuura, Kimitsu, Minamiboso, Mutsuzawawa, Nagara, Onjuku, Otaki	Low sprawl	Good quality

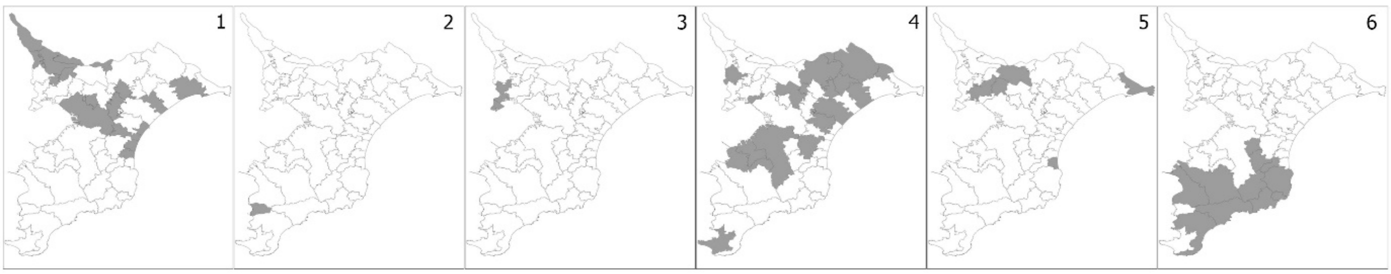

Figure 10. The area where correlated cities have similar urban sprawl and RSEI level.

Generally, urban sprawl has been observed in all the countries. While Japan is experiencing shrinkage sprawl, primarily caused by an aging population, it is important to note that several developed countries have coped with similar situations. Proposal planning to address this issue in Chiba, which is characterized by important greenery and dedicated to ecological preservation, could serve as a valuable reference for these countries. Developing countries amid sprawling development have highlighted the importance of research. Urban development can be pursued, but ecological harmony should be prioritized through compact urban planning. By maintaining balance, these developing nations can develop an awareness of the challenges and successful planning faced by Chiba Prefecture, targeting dense and sustainable urban landscapes for the future.

5. Conclusions

Chiba Prefecture implemented city planning measures, including delineated areas, to promote compact development and limit urban sprawl. The region is known for its abundant natural vegetation, featuring vital ecosystems, such as Satoyama and Satoumi. However, the agriculture, forestry, and fishery sectors face productivity challenges owing to an aging population and shrinking workforce. Preservation of this natural heritage site is crucial for future generations. This study employed spatiotemporal analysis to characterize urban sprawl, assess ecological quality, and examine their relationship in Chiba Prefecture.

This study showed that urban development in Chiba Prefecture extends throughout the region beyond designated areas. Urban sprawl was higher in Chiba than in other Tokyo Metropolitan Area prefectures, but the overall degree was not excessive (approximately 0.5 out of 1). Urban sprawl decreased in the central and fringe areas and increased in the periphery. This indicates a random spread of urban areas away from the central regions. Chiba's fringe and peripheral areas (UCAs and UUAs) play vital roles in vegetation protection and provide ecological benefits. The ecological quality of Chiba moderately increased from 1990 to 2021, scoring 0.5 out of 1. This signifies moderate vegetation coverage, average biodiversity, and a livable environment with some limitations. The highest ecological quality was found in the southern region, particularly in the Boso Peninsula, which is known for its diverse forests, plantations, agriculture, rare species, and abundant food sources, making it a precious natural resort.

The analysis revealed a negative correlation between urban sprawl and ecological quality. However, the increase in urban sprawl and the ecological landscape suggests ongoing urban development toward a sustainable city. Chiba emphasized the creation of a compact city by prioritizing residential and urban functions, elderly care, commercial centers, administrative facilities, and public spaces for community activities and lifelong learning. It is also important to guide land use systematically and establish an industrial platform aligned with ecological improvement. Planning proposals based on this analysis can be applied to similar cities to promote future compact city development in Chiba. This can be a valuable insight for developed countries with similar situations and developing countries pursuing urban development.

6. Limitations

This study focuses specifically on analyzing urban sprawl within a built-up environment and prioritizing urban spatial analysis. The analysis did not include economic and social aspects such as performance management or political implications, which are broader scales for describing urban sprawl. This study relied on a spatial-based remote sensing platform, eliminating the need for fieldwork. In the RSEI analysis, four indices were used to assess ecological quality. Different studies have used various indicators within the RSEI depending on their specific objectives and backgrounds. The initial RSEI proposal found suitable applications in forests, cities, deserts, oases, and other regions. However, based on relevant research, the defined ecological environment quality, represented by these four indicators, was considered sufficient for the study area.

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