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Spatial-Temporal Dynamics of Urban Green Spaces in Response to Rapid Urbanization and Urban Expansion in Tunis between 2000 and 2020

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Abstract: Over the past two decades, the rate of urbanization has increased significantly worldwide, with more than half of the population already living in cities; this trend continues in numerous countries and regions. Tunisia is a North African country with a rich history and diverse cultural heritage. In Greater Tunis, its capital city, urbanization has accelerated since 1960. Rapid urbanization has increased the demand for grey infrastructure and led to changes in land-use patterns and the destruction of the environment. This study aims to understand and depict the relationship between urban expansion and the green infrastructure in the Greater Tunis area. This study uses land-use data, administrative boundaries vector data, and Google satellite imagery datasets to calculate and analyze the changes in the land use transfer matrix and landscape pattern index of built-up land and green spaces in the Tunisian capital for three periods: 2000, 2010, and 2020. We found that the expansion of built-up areas in Tunis has increased from 8.8% in 2000 to 12.1% in 2020, and changes in green spaces have decreased from 23% in 2000 to 20.9% in 2020. Without planning guidelines, the layout of green spaces has become more fragmented and disorganized. For this reason, we provide programs and suggestions for building a complete ecological network of green spaces in order to provide references and lessons for related studies and cities facing the same problems.

Keywords: urban expansion; land use; green space; spatial–temporal dynamics; landscape pattern index; landscape planning

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1. Introduction

Urbanization and rapid urban expansion have become iconic features of the 21st century, changing the physical and social landscape of cities around the world [1]. As the urban population continues to grow, the demand for urban infrastructure and services intensifies, often leading to the neglect of natural or green spaces and resulting in serious urban environmental problems that affect the environment and the well-being of urban residents [2]. Urban green spaces play a crucial role in solving these problems, as well as enhancing urban livability, providing recreational opportunities, reducing environmental risks, and improving the overall quality of life of residents.

Currently, the definitions of urban expansion and urban sprawl vary [3]. Batty et al. defined urban sprawl as "uncoordinated growth: the expansion of communities without regard for consequences" [4]. In 2010, Bhatta et al. wrote that while the exact definition of sprawl is debated, it is widely accepted that urban sprawl is characterized by a pattern of unplanned and uneven growth, which is driven by multiple processes and leads to the inefficient use of resources [5]. Zhou then pointed out that "urban sprawl refers to the phenomenon of uncontrolled expansion and spreading of urbanized areas, which causes urban activities originally concentrated mainly in the central area to spread to the periphery of the city, and the urban form presents the characteristics of dispersion, low density, single regional function, and dependence on automobile traffic". As observed, similar adverse consequences are described in the definitions of the different degrees of sprawl.

Urban expansion is often the result of the coupling of social and economic drivers, natural ecological constraints, neighborhood relations, and other factors [6]. The internal drivers of urban expansion mainly include the upgrading of the city's economic and social development levels, the adjustment of industrial structure, a change in functional positioning, etc., while external drivers include the macroeconomic background, a change in policies, and the input of external funds. Population growth is one of the most "obvious" factors explaining land expansion, and related studies show that population growth has a positive and significant impact on land occupation, but the strength of the impact often varies significantly between unventilated regions or countries [7].

The expansion of the city encroaches upon green areas, resulting in challenges that include informal settlements, deficient services, and traffic congestion in cities. Balancing heritage preservation with modern development becomes crucial. Housing shortages and economic discrepancies emphasize the need for meticulous urban planning. In this context, water scarcity, the degradation of green spaces, and the need to build climate resilience cast a shadow over the future of cities [8,9]. The strain on existing infrastructure is also becoming evident. Therefore, in the situation where urban green space is constantly being squeezed, methods for efficiently reconstructing green space structure, solving urban environmental problems, alleviating disorderly urban expansion, and providing a healthy and comfortable living environment have become a focus of research for urban planners and decision makers [10–12].

In 1972, since the Stockholm Conference on the Human Environment, scientists, planners, and researchers have paid more attention to land cover change. At that time, scientific and technological limitations made detecting land changes in a consistent manner over time difficult, and this severely limited the ability of researchers and scholars to understand and control the drivers and processes of these changes [13].

Currently, the introduction of remote sensing satellites offers the possibility of solving the above-mentioned problems. It provides us with multi-temporal, high-resolution, and complete land information with a time-sensitive, periodic, and comprehensive advantage. After the intelligent analysis of remote sensing images, establishing the changes, classification, and identification of features and forming land information with high value are possible, such as information with respect to quantity, area, perimeter, land type, etc., which has a wide range of application value and development significance for urban detection, management, and planning design [14,15].

The combination of GIS (geographic information system) and RS (remote sensing), by analyzing the temporal sequence changes with respect to land and the relationships between spatial nodes, can accurately obtain the scale, speed, and direction of urban growth, becoming a typical application method for studying urban expansion issues [16,17]. In the simulation model of urban expansion research, cellular automation (AC) can model complex dynamic systems and is widely used due to its simplicity, flexibility, and intuitiveness [18]. AC adopts a discrete grid, presenting complex global behavior using simple local rules and depicting changes in the cell that is under the influence of the neighborhood over a time span. It is often used for conceptual inference with coarse accuracy at the macroscale [19]. Compared with the AC model, the agent-based model (ABM) exhibits a trend of change at the macroscale through the microscopic interaction of units from the bottom to the top. The advantage of this distributed algorithm over the global algorithm is relatively obvious compared to CA [20]. However, performance bottlenecks and design shortcomings are also present from a technical perspective [21].

Although land area, density, and dispersion are important dimensions for measuring land expansion, most studies examine the impact of determinants through these land areas. However, only considering the area dimension may lead to monolithic and one-sided result suggestions, with unpredictable effects on the other dimensions. Landscape indices will effectively compensate for the shortcomings of using a single dimension of area to determine drivers. Fragstats software provides us with hundreds of shape quantification metrics and calculations, most of which evolve from basic morphological metrics, such as patch area, number, density, and average area. It has been shown that the average perimeter–area ratio, contagion, standardized patch shape, patch perimeter–area scaling, number of attribute classes, and large-area scaling are the most comprehensive metrics [22]. In addition, the Fractal Dimension Index and Landscape Division Index will also be widely applied in the field of urban form and landscape patterns with respect to the complexity and fragmentation of patch shapes [23,24].

Tunisia (the Republic of Tunisia) is a North African country bordering the Mediterranean Sea. Tunis is the capital of Tunisia, and it is surrounded by numerous satellite cities, forming a vast region of the Greater Tunis area (Tunis). Tunis's story unfolds in a complex interplay of economic growth, environmental sustainability, and the preservation of its unique cultural identity. The continuous migration and mobility of people have greatly promoted an increase in urban built-up areas over the past few decades. The rapid urbanization and urban sprawl have significantly changed the spatial form of green and grey infrastructure [25]. Inevitably, the shaping of the urban landscape now also faces this set of pressing planning challenges. Consequently, urbanization has attracted more research in recent decades due to the growing prominence of and interest in environmental issues [26].

In the evolution of Tunis, urban change is often closely linked to economic, political, demographic, and social contexts, and this is reflected in the displacement and structural transformation of settlements. In this case, much of the region has taken the form of an informal settlement, and this is manifested by the absence of maps indicating the location and pattern of shacks and buildings [27]; it is a form of the concentrated proliferation of small shelters. This is also an important reason why this study utilizes remote sensing to capture land changes in Tunisia. Tunis as a case study object is a sufficient representative and can clarify the issues and links between urban expansion and green space, which in turn will form a reference for other urban construction projects in Tunisia and North Africa, especially green space optimization.

Urban sprawl is an inevitable process for developing Tunisia. However, there are few studies examining urban expansion in the capital city of Tunisia from a green space perspective, and more literature focuses on examining the causes, dynamics, and impacts of urban expansion. A study by Chabbi and Abid (2008) investigated the urban structure of Tunisia. Their study showed that the city is expanding at a rate of 500 ha per year because of policy failures and the intrusion of settlements into the greenscape and farmland [28]. Another study provides an in-depth examination of the spatial and temporal dynamics of urban sprawl using finer spatial segmentation; in particular, it utilizes sectoral segmentation used by the National Institute for Statistical Studies (NIS) for census zoning. The results of this study show that the expansion trajectories of the Tunis area exhibit two distinct patterns, both of which are intricately linked to the distance from the Central Business District (CBD). The initial pattern is significant in the central part of the city, where residential density decreases as residents extend towards the city's edge, indicating a spreading urbanization trend. The second pattern, which can be observed at the urban fringe, involves the consolidation of secondary residential centers and the integration of the rural sector [29].

This unchecked urbanization process and rapid urban growth pose a major threat to the available agricultural land in the area. In addition, the entire environmental system, which is associated with green spaces, is experiencing increasing scarcity and fragmentation in the region, also reflecting the urgent need for sustainable and green-centered Tunisian urban planning initiatives.

In this context, this study proposes a time series analysis using remotely sensed data to identify urban changes in Tunis over the past two decades, with a focus on the altered and quantified relationship between green space and built-up urban areas. The aim is to shed light on the spatial–temporal dynamics of urban green spaces in Tunis from 2000 to 2020 and their response to rapid urbanization and urban sprawl. By understanding these dynamics, we can develop strategies and interventions to ensure the availability and accessibility of urban green spaces for the well-being and sustainability of cities and their inhabitants:

First, we assess the extent of built-up areas and green space expansion in Tunis over a 20-year period.

Second, we explore the characteristics and patterns of change in Tunis's landscape patterns over a 20-year period.

Finally, we provide planning-level references and recommendations for the future urban development of Tunis city.

The insights gained will enable urban planners, policymakers, and stakeholders to recognize the importance of preserving and enhancing urban green spaces in the face of urban sprawl. In addition, our results provide empirical evidence for supporting decision making with respect to sustainable urban development in Tunis and provide information for cities facing similar challenges.

2. Materials and Methods

2.1. Study Case

The study area selected is the Tunis metropolitan area. Geographically, Tunis is positioned at approximately 36.8065° N latitude and 10.1815° E longitude. It is situated in the northern part of Tunisian territory, and it is adjacent to the Mediterranean Sea. It is situated at the Gulf of Tunis to the northeast, which provides the city with a strategic coastal location. Often referred to as "Greater Tunis", the Tunis metropolitan area covers an area of 260,000 ha, or 2% of the country's total area, and is home to approximately 2.7 million inhabitants. Tunis comprises four governorates, also known as wilayah (Tunisian dialect), which translates to province: Ariana, Ben Arous, Manouba, and Tunis (Figure 1).

Tunis is a natural harbor that has played an important role in the history and development of the country; however, the governance and planning of Tunis have been neglected due to several successive changes in the Tunisian government and leadership over the last decade, and the process of decentralization has not yet been completed [30]. Since the Arab Spring revolutions of 2011, support at the national level has also been uneven, with an insufficient level of engagement between ministries and local authorities and a disconnect between policy intentions and operational levels.

Currently, the Tunisian Ministry of Local Affairs and Environment has been working to improve environmental governance and realities. The government agencies were committed to the global process of combating climate change and respecting sustainability in its model of economic development [31], and they have signed several treaties with different inter-ministerial collaborations to limit the degradation of the country's resources and protect and improve the existing structure of urban green spaces.

2.2. Data Source and Research Framework

In order to quantify the urban sprawl and spatial indicators of Tunis during the 2000–2020 period and the impact of this sprawl on the green urban space more visually, we used land-use data, administrative boundaries' vector data, and Google satellite imagery datasets.

Among them, the land-use data contained three periods of remote sensing satellite images (2000, 2010, and 2020), with 30 m accuracy, and they were obtained from the Globalland30 platform (https://www.webmap.cn/commres.do?method=globeIndex 15 June 2022). The overall accuracy of this dataset exceeds 80% [32], and this dataset has been widely used in many studies on climate detection, land surface change, ecosystem dynamics, and carbon cycles [33,34]. The administrative boundaries were obtained from the open-source dataset provided by ArcGIS Hub (https://hub.arcgis.com/datasets 15 June 2022), and the data were processed in ArcGIS (ArcMap10.7), Fragstats 4.2, and Excel2016.

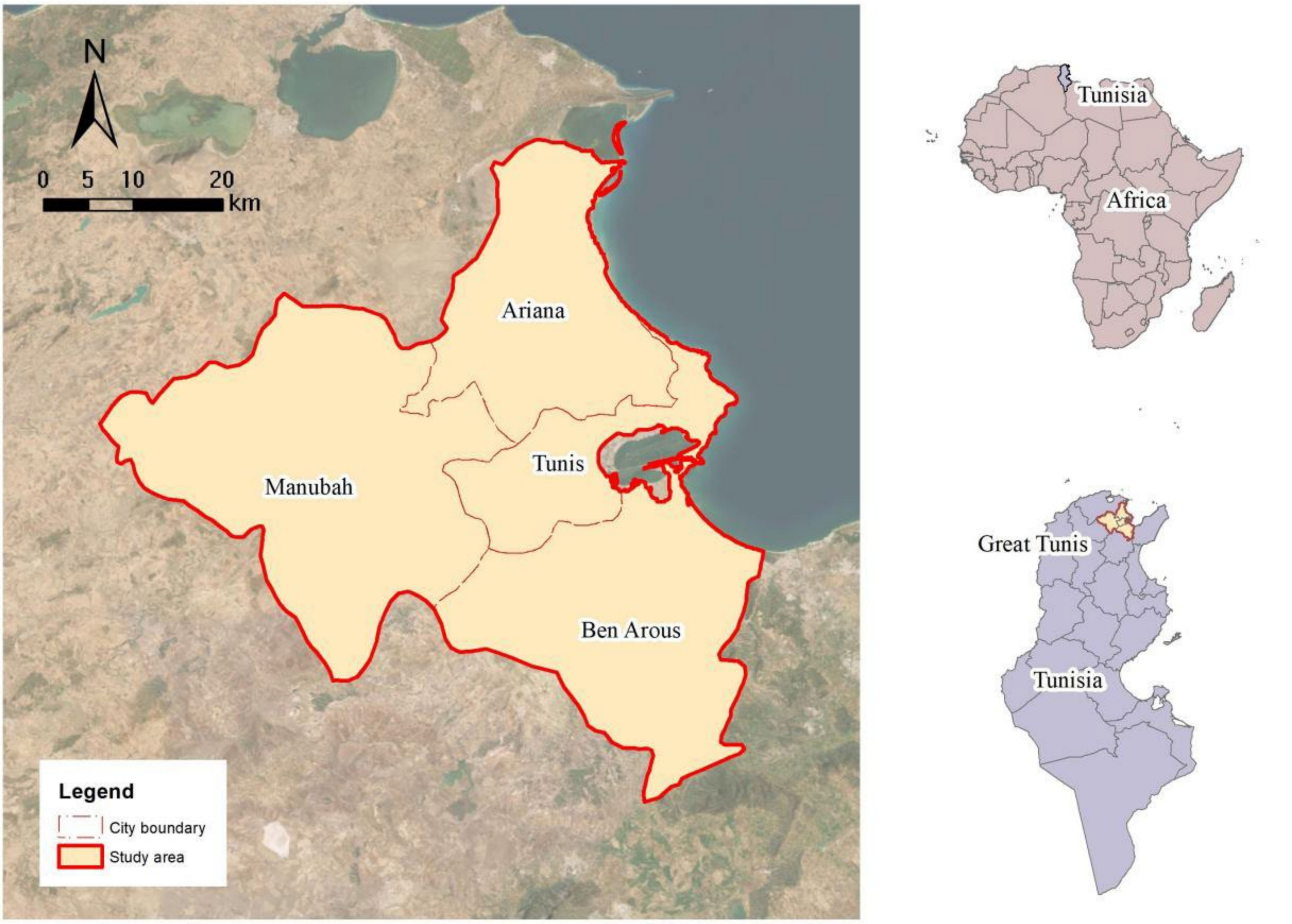

Figure 1. Location of the study area.

The main flowchart of this study is shown in Figure 2. First, remote sensing satellite images and administrative boundary vector data were imported into ArcGIS 10.7 GIS software. Projection correction and coordinate transformation were performed on satellite image raster data and administrative boundary vector data based on 32 zones and datums of the World Geodetic System (WGS) WGS84. Land-use satellite images were masked according to the administrative boundary vector data of the capital region of Tunisia (Tunis). With respect to extraction, according to the classification system code of the data source, the land-use types were categorized into nine categories: bare land, grassland, cropland, scrub, wetland, marine, water body, and construction land.

The land-use transfer matrix and landscape pattern index can reveal the conversion relationship between land-use types and the characteristics of green spatial pattern changes in the study area within a specific period of time, which can provide a comprehensive understanding of the total land-use changes and information on the dynamic process, and this can also be combined with the graphical language to summarize the spatial evolution law [22]. Landscape pattern index analysis was carried out using Fragstats 4.2 software to study the changes in artificial land surface and green infrastructure over time. Finally, the results of the analysis of the land-use transfer matrix, landscape pattern index, and population change in the Tunisian capital region (Tunis) from 2000 to 2020 were used to explore the degree of damage to green spaces and make recommendations for the protection and construction of green infrastructure in Tunis.

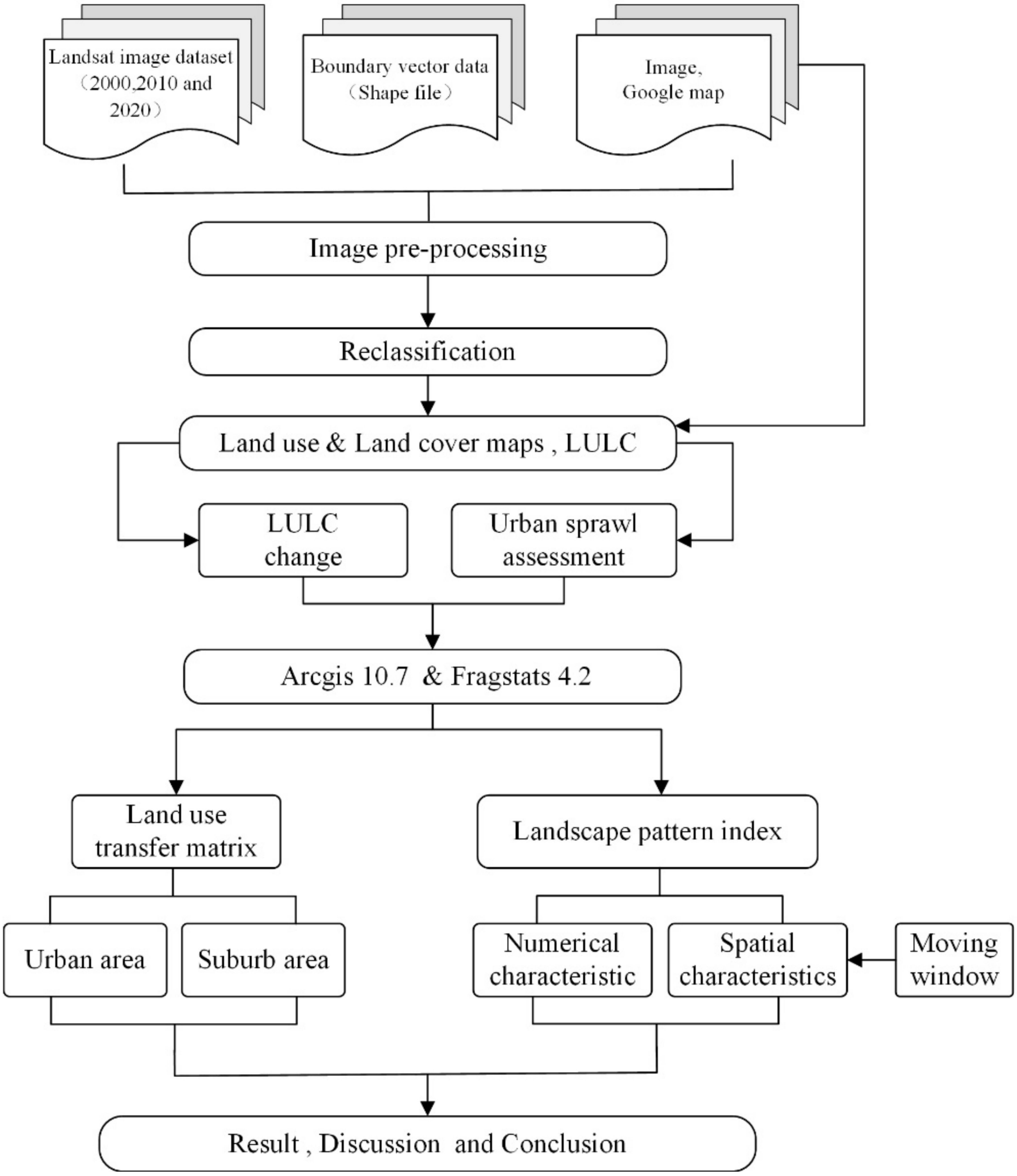

Figure 2. Research framework.

2.3. Data Processing

2.3.1. Land-Use Transfer Matrix

The land-use transfer matrix can reveal the transformation relationship between land-use types in the study area within a certain period, which can visualize the overall change in land-use types, providing rich dynamic process information, and it can also be combined with graphical information to summarize the spatial evolution law [35]. In order to understand the transformation between different land-use types in Tunis over a period of two decades and further analyze the pattern of change and its intrinsic causes, a quantitative description of the transformation of land types was used in this study using a land-use transfer matrix, and its formula is as follows [36],

$$S_{ij} = \begin{vmatrix} S_{11} & S_{12} & \dots & S_{1n} \\ S_{21} & S_{22} & \dots & S_{2n} \\ \dots & \dots & \dots & \dots \\ S_{n1} & S_{n2} & \dots & S_{nn} \end{vmatrix}$$

where S denotes the area, n denotes the number of land-use types before and after the transfer, and i and j denote the land-use types before and after the transfer, respectively. sij denotes the area that transformed from land type i to land type j before the transfer. Each row element in the matrix represents the flow of information from land type i before the transfer to each land type after the transfer, while each column element represents the source information of land type j after the transfer from each land type before the transfer.

Based on the vector information of land-use changes in Tunis in 2000, 2010, and 2020, the land-use data for the three time periods of 2000–2010, 2010–2020, and 2000–2020 were established in the land-use type field. The data of each of the 2 periods were intersected and analyzed. Then, the area field was added, the geometry was calculated, and a pivot table was used in Excel 2016 to generate the land-use transfer matrix, quantitatively analyzing the transformation between land types.

2.3.2. Landscape Pattern Index

The landscape pattern index can reflect the structural composition and spatial configuration information of the landscape relatively accurately, and it is a simple quantitative index. According to the object's description level, it can be divided into the patch-level index, patch-class-level index, and landscape-level index [37]. Because there are many indices that quantitatively describe landscape characteristics and many landscape indices have different degrees of correlation with each other, there is redundancy in expressing landscape pattern characteristics. Therefore, in this paper, we mainly study the dynamic trend of land-use landscape patterns in Tunis at two levels: (1) Area of class (CA), number of patches (NP), mean patch size (MPS), patch density (PD), landscape division index (DIVISION), and fractal dimension index (FRAC) are selected at the class level, and (2) patch cohesion index (COHESION), landscape aggregation index (AI), Shannon's diversity index (SHDI), and landscape contagion degree (CONTAG) are selected at the landscape level, which are described in Tables 1 and 2. Landscape pattern indices were calculated via Fragstats 4.2 software with a raster cell size of 30 m × 30 m.

Table 1. Definition of the landscape index at the class level.

Landscape Pattern Index	Ecological Implications	Calculation Formula	Parameter Description
CA	Total area of landscape patches	$CA = A_i$	A_i = total area of the patches
NP	Number of landscape patches	$NP = N_i$	N_i = number of the patches
MPS	Average area of individual patches in the landscape	$MPS = \frac{A_i}{N_i}$	A_i = total area of the patches; N_i = number of the patches
PD	Number of patches per unit area (density of patches)	$PD = \times 100 \frac{N_i}{A_i}$	A_i = total area of the patches; N_i = number of the patches
DIVISION	Indicator describing the degree of separation of landscape structures	$DIVISION = \left[1 - \sum_{j=1}^{m} \left(\frac{a_{ij}}{A}\right)^2\right]$	a_{ij} = area of the patch; A = total landscape area
FRAC_MN	Measure of the complexity of the edge shape of a landscape	$FRAC = \frac{2\ln\left(0.25p_{ij}\right)}{\ln a_{ij}}$	p_{ij} = perimeter of the patch; a_{ij} = area of the patch

Table 2. Definition of the landscape index at the landscape level.

Landscape Pattern Index	Ecological Implications	Calculation Formula	Parameter Description
COHESION	Degree of spatial cohesion between patches	$\text{COHESION} = (100)\left\lfloor 1 - \frac{\sum_{i=1}^{m}\sum_{j=1}^{n} p_{ij}}{\sum_{i=1}^{m}\sum_{j=1}^{n} p_{ij}\sqrt{a_{ij}}} \right\rfloor \left\lfloor 1 - \frac{1}{\sqrt{Z}} \right\rfloor^{-1}$	p_{ij} = perimeter of the patch; a_{ij} = area of patch j; Z = total number of pixels in the landscape
AI	Concentration of patches in a landscape. The higher the value of the clustering index, the more clustered the patches in the landscape	$\text{AI} = \left\lfloor \frac{g_{ii}}{\max - g_{ii}} \right\rfloor (100)$	g_{ij}= number of like neighbors (connections) between pixels of the patch according to the single count method; max-g_{ij} = maximum number of like neighbors (connections) between pixels of patches based on the single count method
SHDI	Reflects the richness of the landscape	$\text{SHDI} = -\sum_{i=1}^{n} (P_i \text{In} P_i)$	P_i = proportion of patch types in the landscape; n = number of patch types in the landscape
CONTAG	Reflects the degree of landscape agglomeration or extension trend	$\text{CONTAG} = \left\{ 1 + \frac{\sum_{i=1}^{m} \sum_{k=1}^{m} \left[P_i \times \frac{g_{ik}}{\sum_{k=1}^{m} g_{ik}} \right] \times \left[\text{In}\left(P_i \times \frac{g_{ik}}{\sum_{k=1}^{m} g_{ik}} \right) \right]}{2\text{In}(m)} \right\} (100)$	P_i = proportion of type patches in the landscape; g_{ik} = number of neighbors between patch types i and k based on the double counting method; m = number of patch types in the landscape

2.3.3. Moving Window Method

The moving window method is widely used in geospatial data analysis. The core idea is to define and slide a fixed-size window onto the dataset and generate a raster map by calculating the landscape pattern indices within the window in order to observe the spatial variability of the landscape pattern in depth [38]. Compared with the traditional method of overall characterization, the moving window method can realize the precise quantification and intuitive visualization of landscape indices with respect to the local area, which can help present the dynamic evolution process of spatial landscape patterns more clearly and reveal the variability of the internal structure of the landscape [39].

According to the representative significance of the research landscape indices and previous studies, this paper selected MPS, PD, FRAC, and DIVISION to analyze the spatial heterogeneity characteristics of the landscape pattern from each of the above nine landscape indices. Changes in the laser pattern of Tunis were explored in terms of green areas (woodlands, grasslands, and shrubs) and built-up areas. The choice of the moving window scale is crucial for the accuracy of results [40,41]. Based on the fact that previous researchers in the study of municipality-scale cities mostly used a 1 km grid for slicing and dicing, this paper also selected 1 km as the unit scale to study the regional landscape pattern [42].

In Fragstats 4.2, continuous raster maps of landscape indices for 2000, 2010, and 2020 were calculated using the moving window method. Then, Arc GIS 10.7 was utilized to calculate the mean values of the changes in each landscape pattern index for the years 2000–2010, 2010–2020, and 2000–2020. The change values of landscape pattern indices were also categorized into five classes using the Jenks natural breakpoint hierarchy. A cut-off point of 0 indicates no change in landscape pattern, greater than 0 indicates an increase in value, and less than 0 indicates a decrease in value.

3. Results

3.1. Land-Use Types: 2000–2020

As shown in Figure 3, cropland is the land type with the largest share in the entire region, the built-up area is concentrated in the eastern region, and forestland is concentrated in the southeast, with a small concentration in the south and the west. Shrublands are mainly distributed in the south of Tunis and fragmented in the center and west, and grasslands are fragmented in the center. The overall land-use types in Tunis have changed gently over the past two decades, with built-up areas spreading along the center of the city, grassland extending linearly in the south, and shrubland diminishing significantly in the west, due to conversion to bare land.

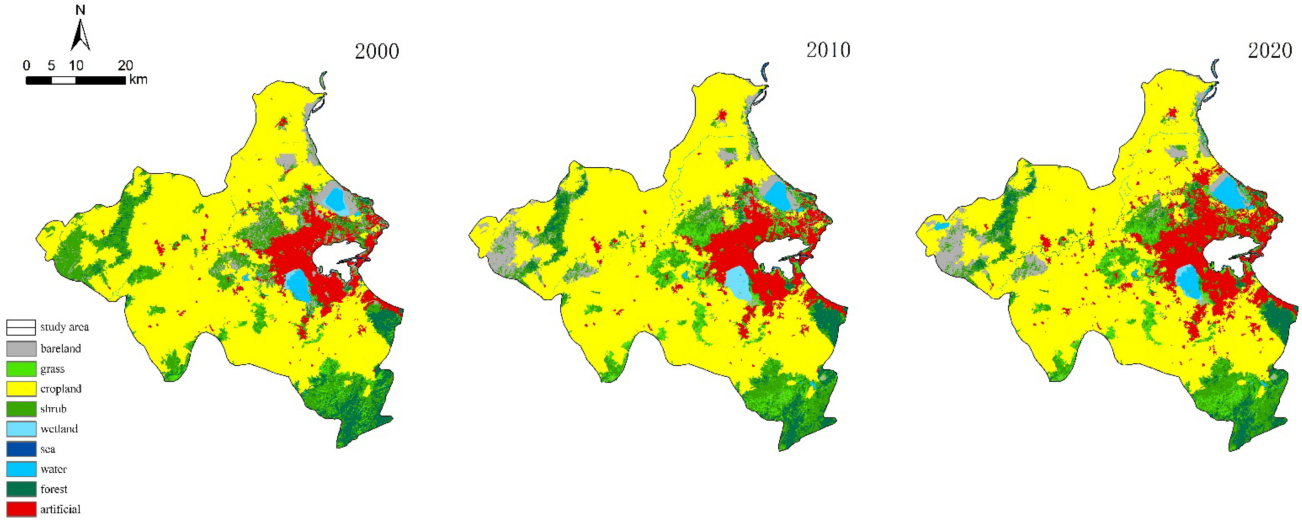

Figure 3. Land-use/cover change in Tunis in 2000, 2010, and 2020.

According to the statistics (Table 3), in 2000, built-up land accounted for 8.8% of the total area, and green space consisting of forest, shrubs, and grassland accounted for 23.0% of the total area; in 2010, built-up land accounted for 9.8% of the total area, and green spaces accounted for 21.4% of the total area; in 2020, built-up land accounted for 12.1% of the total area, and forests, shrubs, and grasslands accounted for 20.9% of the total area.

Table 3. Statistics on land-use area changes in Tunis.

Land-Use Type	2000 (km^2)	2010 (km^2)	2020 (km^2)	Change (km^2)		
				2000–2010	2010–2020	2000–2020
Cropland	1544.07	1550.95	1505.92	6.88	−45.03	−38.15
Forest	135.43	116.08	116.55	−19.35	0.47	−18.88
Grass	52.63	119.59	110.55	66.96	−9.04	57.92
Shrub	391.43	300.92	298.91	−90.51	−2.01	−92.52
Wetland	8.86	23.96	6.11	15.1	−17.85	−2.75
Water	37.71	26.78	54.38	−10.93	27.6	16.67
Artificial	222.58	245.44	305.08	22.86	59.64	82.50
Bare land	121.82	130.67	117.29	8.85	−13.38	−4.53
Sea	1.50	1.69	1.20	0.19	−0.49	−0.3

From 2000 to 2010, shrubland in Tunis underwent the most noticeable changes among land cover types, followed by grassland. Shrubland decreased by 90.5 km^2 over the decade, with a significant conversion to grassland, cropland, and forest land (Table 3). Grassland increased by 67 km^2, and this was mainly due to conversions from shrubland and bare land. Built-up areas experienced a slight growth, primarily due to the conversions of shrubland and bare land, while forest land slightly decreased. Other land cover type conversions exhibited relatively smaller areas of change (Table 4).

From 2010 to 2020, the cropland area decreased by 45 km^2, with the area converted out surpassing the area converted in, primarily transforming into built-up areas. Urban land expansion increased by 59.5 km^2, originating from conversions of cropland and bare land. There was a slight increase in the water body area, while the wetland area slightly decreased (Table 5).

During the 20-year period, the trend of land-use change in Tunis was slow and maintained a relatively stable state. Grassland areas increased by 57.9 km^2, and built-up land expanded by 82.5 km^2, mainly occupying the original cultivated land and shrubland. The area of shrubland decreased sharply by 92.5 km^2, the area of cultivated land decreased by 38.1 km^2, the area of water bodies increased slightly, and the area of forest land decreased slightly. In the process of urbanization, built-up areas have continued to increase, and the area of shrubland has decreased, while cultivated land, grassland, wetland, and bare land have exhibited a tendency to increase and then decrease; moreover, forest land and water bodies have shown a tendency to decrease and then increase (Table 6).

Table 4. Land-use transfer matrix of Tunis from 2000 to 2010.

2000–2010	Cropland	Forest	Grass	Shrub	Wetland	Water	Artificial	Bare Land	Sea	Sum
Cropland	1500.67	1.87	6.71	20.09	0.13	2.20	8.17	2.75	0.01	1542.61
Forest	2.77	79.59	4.74	45.18	0.22	0.38	1.65	1.39	0.06	135.98
Grass	3.58	2.18	19.93	21.02	0.01	0.50	1.24	5.00	0.31	53.78
Shrub	28.76	24.28	65.51	181.27	0.31	0.68	14.89	73.28	0.02	389.01
Wetland	0.00	0.10	0.19	0.01	3.15	4.90	0.10	0.42	0.00	8.87
Water	0.84	0.72	0.25	0.30	19.14	15.88	0.42	0.17	0.00	37.72
Artificial	5.85	0.47	2.96	2.75	0.02	0.21	207.86	1.80	0.06	221.98
Bare land	7.22	6.85	19.51	29.57	0.95	1.93	10.20	46.27	0.50	123.00
Sea	0.01	0.22	0.01	0.01	0.00	0.03	0.26	0.23	0.66	1.42
Sum	1549.71	116.29	119.81	300.19	23.95	26.72	244.79	131.30	1.62	2514.37

Table 5. Land-use transfer matrix of Tunis from 2010 to 2020.

2010–2020	Cropland	Forest	Grass	Shrub	Wetland	Water	Artificial	Bare Land	Sea	Sum
Cropland	1483.17	2.72	2.40	6.30	0.01	4.89	40.37	10.15	0.01	1550.01
Forest	0.75	96.35	0.76	16.05	0.00	0.99	0.97	0.38	0.02	116.27
Grass	2.41	0.92	81.73	19.85	0.04	0.72	11.19	2.99	0.00	119.84
Shrub	6.19	15.65	20.10	238.77	0.01	0.33	9.62	9.59	0.00	300.25
Wetland	0.10	0.00	0.05	0.02	5.79	17.70	0.26	0.03	0.00	23.95
Water	1.51	0.29	0.30	0.53	0.00	23.70	0.14	0.24	0.00	26.71
Artificial	4.52	0.45	2.36	6.73	0.13	0.26	229.89	0.33	0.07	244.75
Bare land	6.03	0.41	3.35	10.12	0.15	5.69	11.85	93.49	0.17	131.28
Sea	0.00	0.05	0.02	0.01	0.00	0.04	0.06	0.53	0.86	1.57
Sum	1504.68	116.84	111.06	298.38	6.12	54.32	304.34	117.73	1.14	2514.61

Table 6. Land-use transfer matrix of Tunis from 2000 to 2020.

2000–2020	Cropland	Forest	Grass	Shrub	Wetland	Water	Artificial	Bare Land	Sea	Sum
Cropland	1465.90	2.95	4.17	15.94	0.02	5.27	41.30	7.56	0.02	1543.12
Forest	1.89	84.86	3.41	42.40	0.21	0.32	1.92	0.98	0.02	136.01
Grass	2.21	1.97	21.91	19.58	0.01	0.42	2.21	5.36	0.12	53.79
Shrub	24.46	19.98	62.62	186.86	0.36	0.79	27.69	66.36	0.02	389.13
Wetland	0.00	0.02	0.03	0.00	2.89	5.66	0.26	0.01	0.00	8.87
Water	0.72	0.48	0.22	0.19	1.62	33.85	0.35	0.28	0.00	37.71
Artificial	3.55	0.05	1.52	5.54	0.00	0.14	210.78	0.39	0.00	221.98
Bare land	6.17	6.46	17.19	27.91	1.01	7.72	19.76	36.66	0.32	123.18
Sea	0.00	0.14	0.02	0.00	0.00	0.16	0.16	0.23	0.68	1.40
Sum	1504.90	116.91	111.08	298.43	6.12	54.33	304.42	117.83	1.17	2515.19

3.2. Analysis of the Spatial Transfer of Building Land and Green Space from 2000 to 2020

3.2.1. Analysis of the Spatial Transfer of Building Land

During the 20-year period, the spatial change in built-up areas was mainly concentrated in the eastern central city. Due to the dense population and convenient transportation in the central urban area, the simultaneous rapid development of urbanization, human activities—such as infrastructure construction and public facility support—and the implementation of urban development strategies, the built-up area underwent significant expansion.

From 2000 to 2010, the built-up area increased more slowly, was more concentrated in the east, and increased in a fragmented manner in the central region (Figure 4a), although it decreased sporadically in the north but not significantly.

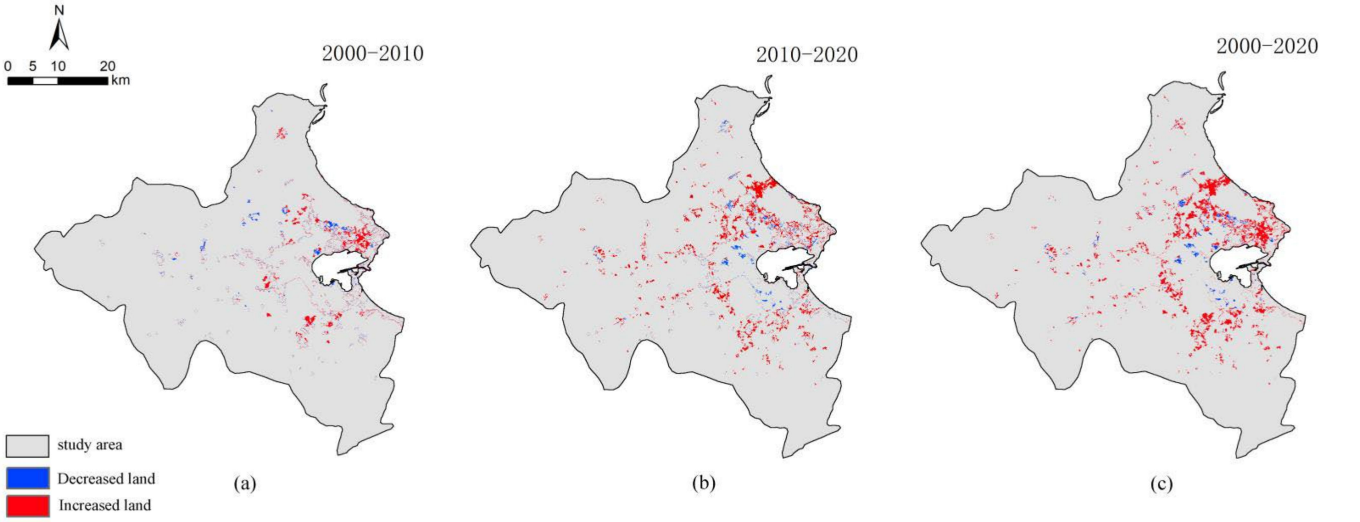

Figure 4. Spatial distribution of changes in built-up land in Tunis (**a**) changes in built up land between 2000 and 2010; (**b**) changes in built up land between 2010 and 2020; (**c**) changes in built up land between 2000 and 2020).

From 2010 to 2020, the built-up area around the Lake of Tunis (in a ring shape) increased significantly along the two east–west highways, exhibiting a linear extension, and the northern area exhibited the most intensive increase and was the most significant (Figure 4b); a reduction in the built-up area was also concentrated around Tunis's Lake, but compared to the increase in the size of the built-up area, it is negligible.

During the 20-year period, the increase in built-up land in the urban area of Tunis was significant and concentrated in the latter decade, with a circular expansion in the eastern part of the region and a linear increase in the central part of the region (Figure 4c).

3.2.2. Analysis of Spatial Shifts in Green Spaces

The period from 2000 to 2010 was a decade of significant changes with respect to the pattern of green spaces in Tunis. In the western suburbs, green spaces decreased in patches, with small fragmented abatements in the northern and southern areas that are adjacent to urban areas; green spaces in the central and northern parts of Tunis exhibited an increase with respect to small, disjointed patches, while in the west and south, they increased in a sporadic manner (Figure 5a).

Between 2010 and 2020, green space changes in Tunis were weak and mainly concentrated in built-area scale shifts, with less pronounced increases and decreases (Figure 5b). There is a small amount of fragmented urban green space additions in the east-central region and likewise, a small amount of fragmented green space reductions at its periphery.

Overall, the increase in green space in Tunis and the decrease in the suburbs over the 20-year period is significant in urban areas (Figure 5c). Urban green spaces show an overall increase followed by an overall decrease, while suburban green spaces show a continuous decrease during the 20 years (Figure 5).

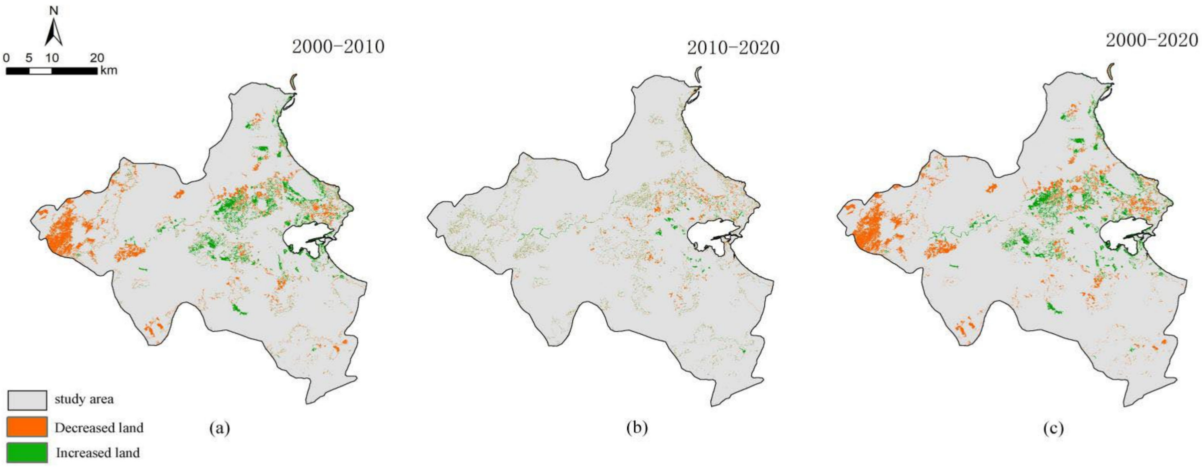

Figure 5. Spatial distribution of changes in green space land use in Tunis (**a**) changes in green space between 2000 and 2010; (**b**) changes in green space between 2010 and 2020; (**c**) changes in green spaces between 2000 and 2020).

3.3. Characteristics and Changes in the Landscape Patterns of Built-Up Land and Green Spaces between 2000 and 2020

3.3.1. Landscape Index Characteristics

With respect to green space, CA decreased from 57,914.73 km^2 in 2000 to 52,671.78 km^2 in 2020 (Table 7), and NP decreased from 2441 to 2184. PD declined slightly, and MPS increased slightly. DIVISION showed slight fluctuations, with an upward and then downward trend, indicating that from 2000 to 2010, green spaces tended to be decentralized; from 2010 to 2020, the centralized contiguity of green space areas increased.

Table 7. Green space landscape pattern index at the class level in 2000, 2010, and 2020.

Year	CA	NP	PD	MPS	FRAC_MN	DIVISION
2000	57,914.73	2441	4.21	23.73	1.0596	0.8654
2010	53,711.82	2219	4.13	24.21	1.0595	0.8709
2020	52,671.78	2184	4.15	24.12	1.0600	0.8620

In contrast, the built-up area experienced significant growth, with CA increasing from 22,210.74 km^2 in 2000 to 30,447.18 km^2 in 2020, an increase of 37% (Table 8). MPS and NP increased while PD also increased gradually, and the separateness index showed a continuous decrease, indicating that the built-up space exhibited a trend of centralization. The changes in FRAC were smaller, with a general decreasing trend, indicating that the shape of the patches in the built-up area is relatively simple and tends to be further simplified.

Table 8. Landscape pattern index of built-up areas at the class level in 2000, 2010, and 2020.

Year	CA	NP	PD	MPS	FRAC_MN	DIVISION
2000	22,210.74	197	0.8870	112.74	1.1041	0.5537
2010	24,494.94	158	0.6450	155.0313	1.1046	0.5045
2020	30,447.18	289	0.9492	105.35	1.0869	0.5112

In terms of landscape indicators, the overall values did not change much. CONTAG showed a decreasing trend from 69.78 to 69.20, which indicated that the landscape showed a certain trend of fragmentation. SHDI increased slightly, with an increase in the degree of diversity. AI remained relatively stable, which indicated that there was no major change in the cohesion between the landscape patches. COHESION increased slightly, which indicated that the degree of connectivity of the landscape was slightly increased (Table 9).

Table 9. Landscape pattern index at the landscape level in 2000, 2010, and 2020.

Year	CONTAG	SHDI	AI	COHESION
2000	69.7758	1.2584	96.8942	99.5950
2010	69.4899	1.2763	97.1742	99.6608
2020	69.2037	1.2864	97.1659	99.6586

3.3.2. Changes in Landscape Patterns

It was observed that the landscape pattern of each area in the study area exhibited phase differences before and after 10 years.

Between 2000 and 2010, the changes in built-up areas were mainly concentrated in urban areas (red area in Figure 3). Among the four indicators, only MPS exhibited an increasing trend, and the high-value areas were mainly distributed at the edge of the urban area, while PD, FRAC, and DIVISION exhibited a decreasing trend. This indicates that the built-up area is expanding outwards, showing an overall increasing trend within the built-up area. Between 2010 and 2020, the change in built-up areas was more dramatic, MPS, PD, and FRAC all increased significantly, and the high-value areas were mainly clustered in the north, west, and south of the built-up area. During a period of 20 years, the MPS increased significantly, and the overall change in built-up area is shown by the filling of the internal area and the expansion of the fringe zones, which is mainly due to the acceleration of the urbanization process.

Between 2000 and 2010, the mean patch size of green spaces in urban areas increased significantly (Figure 6a), the density of patches decreased significantly (Figure 6b), the FRAC value decreased (Figure 6c), and the degree of separation decreased significantly (Figure 6d). This indicates that small-scale green spaces in urban areas continued to merge, green space connectivity increased, and the shapes gradually became simpler. However, suburban green spaces show the opposite trend. There is a significant increase in the fragmentation of suburban green spaces, especially in the western part of the suburbs, and the shape of green space patches tends to be more complex. Between 2010 and 2020, MPS and FRAC remained relatively stable, but unlike the previous 10 years, the DIVISION index of urban green space increased, indicating that urban green spaces gradually tended to become fragmented. During the 20-year period, urban green spaces showed a tendency to be concentrated and contiguous, and the shape of green spaces on the edge of the urban area varied considerably, with the emergence of a low FRAC value, indicating that the shape of the green space tended to be regular. The high DIVISION value was mainly concentrated in the western and southern suburbs, and green spaces tended to be fragmented (Figure 6).

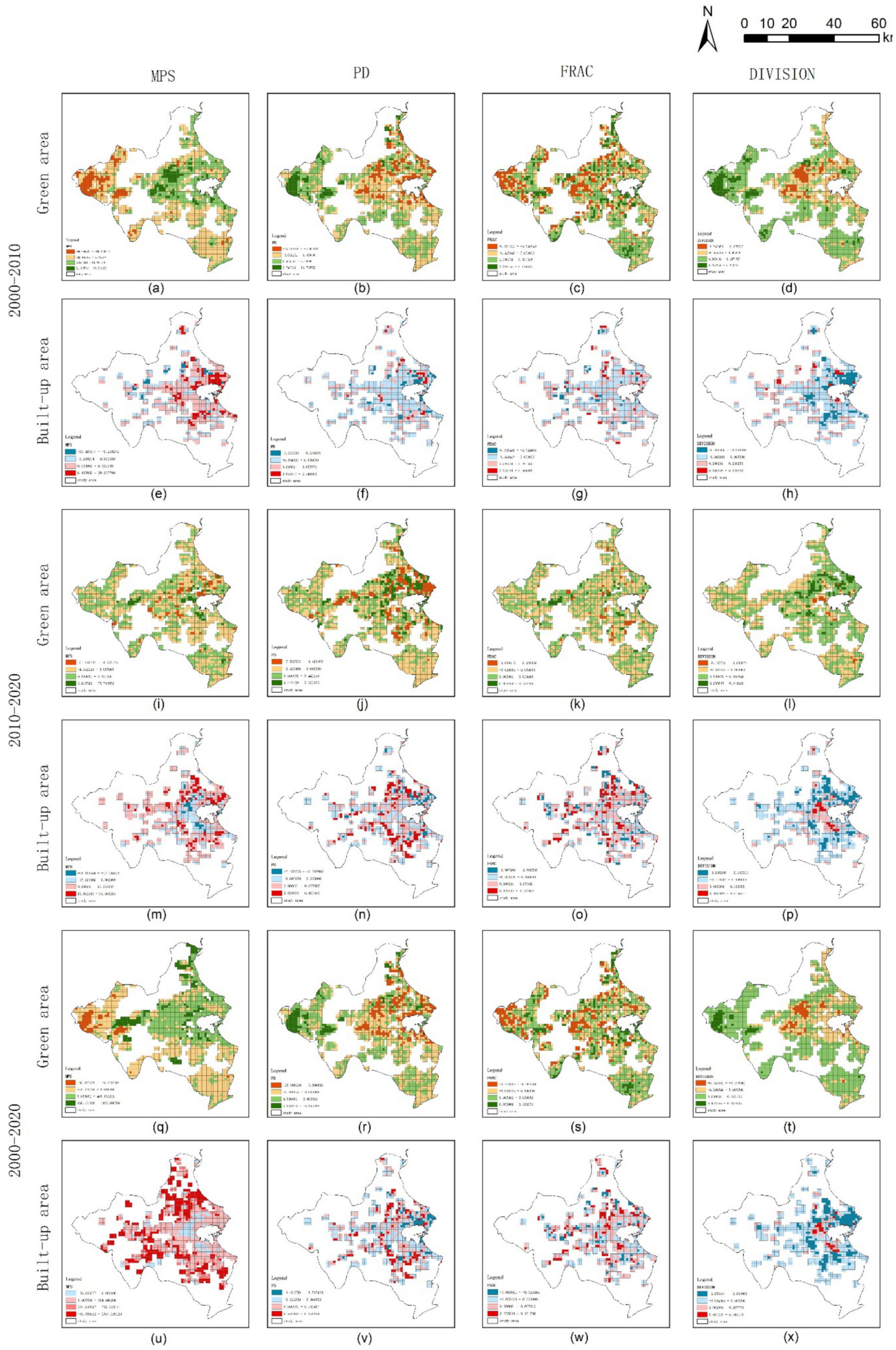

Figure 6. Spatial distribution of changes in landscape pattern indices in Tunis (2000–2020). The lignes can be divided into three section; First is from 2000 to 2010; second is from 2010 to 2020 and the third is from 2000 to 2020, each section has two lignes: built up area and green area. The colums each represents a different landscape pattern index (MPS, PD, FRAC, and DIVISION. Example: (**f**) represents the PD of of built-up area between 2000 and 2010, (**k**) represents Frac of green space between 2010 and 2020, (**u**) represents the MPS of built-up area between 2000 and 2020).

4. Discussion

4.1. Characteristics and Trends of the Expansion of Built-Up Areas in Tunis

According to Figure 7, urban sprawl has exhibited a clear trend over the 20-year period. It can be summarized as follows:

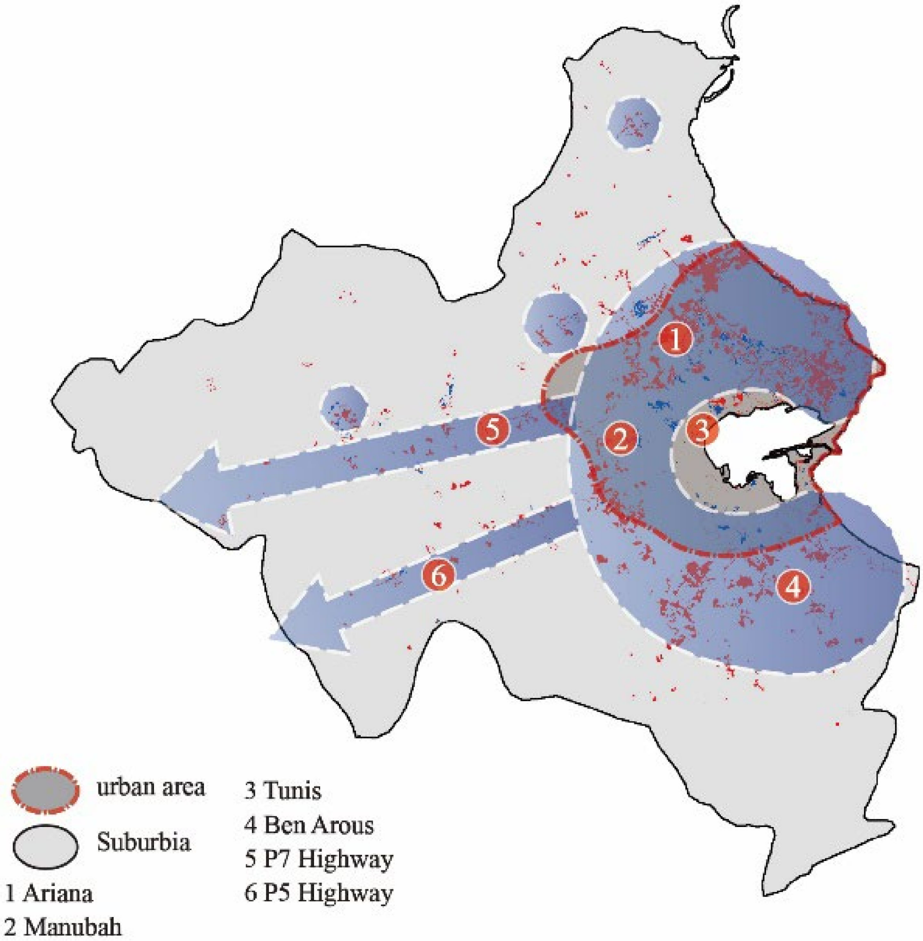

Figure 7. Map of the expansion pattern of built-up areas in Tunis.

Concentric circle expansion: Tunis exhibits a pattern of urban expansion in concentric circles centered on the "Medina" and ringed by Ariana, Manouba, Tunis, and Ben Arous. The Medina was founded in 698 and continued to grow throughout the Middle Ages to become the religious, cultural, and economic center of Tunis, and it will continue to maintain its unique centrality for a long time to come; thus, this concentric pattern of expansion will also continue for a long time to come.

Ribbon extension: Linear development occurs along major transport corridors, such as freeways (P5 and P7 freeways) or roads that are products of how urbanization has occurred at the expense of agricultural land (Sidi H'cine, Mnihla, Douar Hicher, Soukra, Ariana Nord, and Raoued). This dispersed and extended road network structure has induced a large built-up area in the form of a belt that stretches from the center of the city of Tunis to the west.

Satellite sprawl: Between 2000 and 2020, numerous small urban areas emerged on the periphery of the ring, which are scattered around the center of city-like satellite towns.

Multi-nodal development: Multiple urban centers or nodes on the periphery of Tunis have been connected to the main building by a network of light transportation (light metro and buses), creating a pattern of development that is dispersed in all directions.

4.2. Changing Characteristics and Development Trends of Green Spaces in Tunis

Tunis's green space experienced a significant decrease between 2000 and 2010, but there was a trend of increasing and decreasing green spaces between 2010 and 2020. Compared to the significant reduction in green spaces in Tunis between 1950 and 2000 [9,25], the overall rate of reduction has slowed down since 2000. The general trend shows an increase at two sides and multiple points, as well as a decrease at one side and multiple points.

Expansion on two sides mainly occurred in the north and east of the urban area. These two areas are located in the north of the Manouba governorate in the mountain range and in the plains west of EI Habibia, and the expansion does not comprise an artificially planned addition to the built-up area but a natural ecological green space dominated by herbaceous plants.

Multiple points of scattered growth: In the northern part of the built-up area, Kelaat El Andalous and Protville comprise two main points with respect to small growth, and they are still predominantly natural areas. In the southern part of the built-up area, EI Mourouj, Burj Bash Mamluk, Ben Arous, El Mallaha, and other sites are carrying out new green space construction; these are mostly inner-city green spaces, and they are purposefully built (Figure 8).

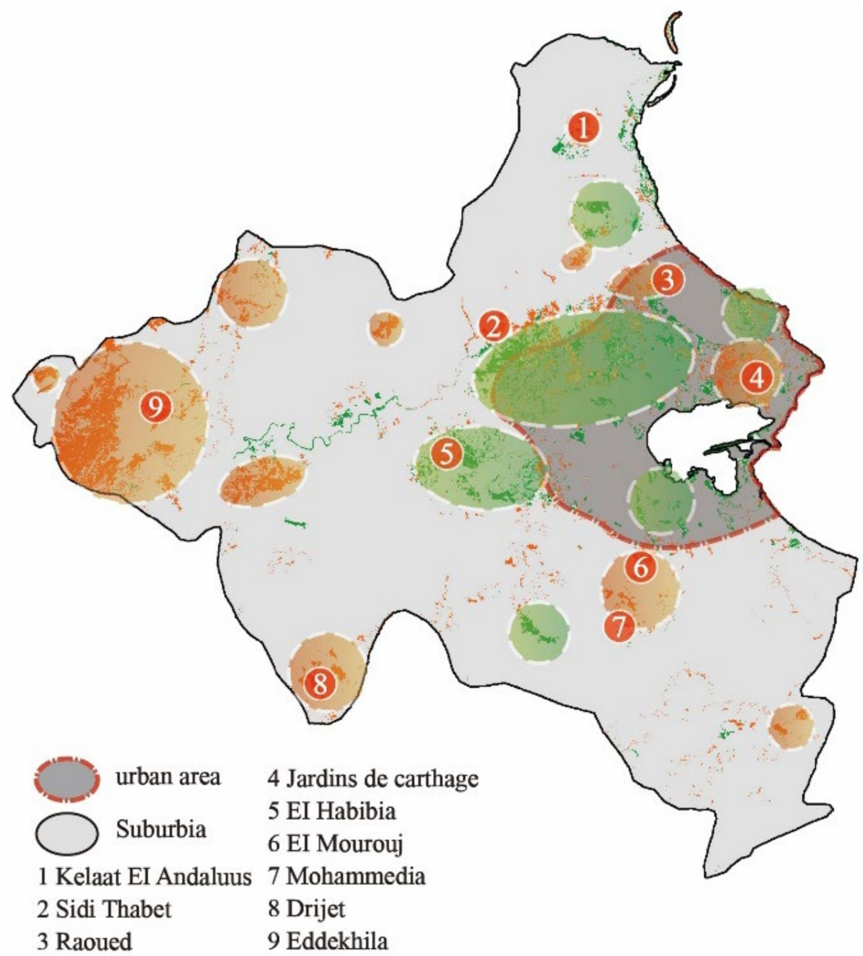

Figure 8. The trends of green space systems in Tunis.

In the western part of the suburb, the area of Eddekhila lost a large area of natural green space to wasteland and agricultural land between 2000 and 2010.

The disappearance of multiple points: Large fragmented natural green areas in the north of the urban area and the south and west of the suburbs were transformed into built-up and agricultural lands, which are mainly located around Raoued, Sidi Thabet, EI Mourouj, Mhammedia, etc.; these are emerging urban areas.

4.3. Lack of Rational Urban Planning Strategies Is the Main Reason for the Blind Expansion of Tunis

Our results demonstrate that the green layout in Tunis has become more fragmented, and the size of green spaces has become smaller. This is due to the transformation of green spaces into built-up areas and the lack of systematic and implementable green infrastructure planning. The increasing number of built-up areas in Tunis, especially during the second part of the timeline, reflects the absence of a strategy that exposes the incompetence of responsible entities in managing urban sprawl and protecting green infrastructure.

Indeed, the documents provided by the Greater Tunis Urban Agency are insightful in terms of urban planning, but the most recent urbanization report was published in 2010, leaving us with a 10-year data and information gap on urban planning and future expansion. Since 2002, the Greater Tunis city government has not issued a robust and sustained urban development planning program. In a 2002 urbanization report issued by the Urban Agency of Greater Tunis (UAGT), city planners recommended decentralizing the capital to the suburbs and planned for several smaller centers, each with its amenities and services. With the construction of these major projects (Ennasr, Jardin del Manzah, Centre Urbain Nord, and Les Berge du Lac sud), the rapid expansion of the city and the creation of polycentric cities have severely damaged the green landscape pattern of Tunis.

4.4. Building a Complete Network of Green Space Systems Is an Urgent and Prominent Issue in Tunis

Tunis, with its long history and culture, is the largest metropolis in the country and the most influential city. Developing a plan for maintaining and connecting urban parks and green spaces can significantly contribute to creating green–blue infrastructure in Tunis (Figure 9).

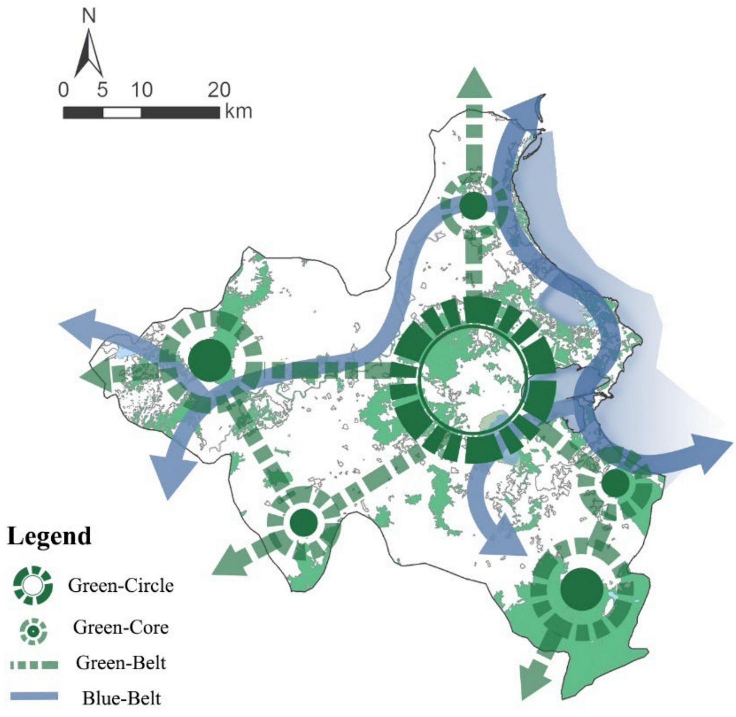

Figure 9. Suggested green blue infrastructure.

By enhancing existing parks—such as Ennahli in Ariana, Farhat Hached in Radès, El Mourouj, etc. (that have experienced a noticeable deterioration characterized by a significant decline in the quality of facilities and equipment, as well as degradation in cleanliness and maintenance [43])—and green spaces, creating green corridors, implementing rooftop greening, and promoting community engagement, Tunis can foster a more sustainable and interconnected urban environment. However, there are challenges to consider, such as limited space in the historic Medina, the need to preserve heritage, water management in a water-scarce region, community engagement, securing funding and resources, and ensuring the effective maintenance and management of green–blue infrastructure projects.

This study suggests maintaining green cores, such as urban parks and communal gardens, creating a green circle around them to provide a second layer of security and continuance, connecting these green cores via a green belt to merge the green structure that in turn contains the city, and providing a safe, natural, sustainable, and more livable city.

One of the challenges of creating and maintaining green infrastructure is water scarcity. Even though Tunis is a coastal city blessed with multiple water bodies, such as the Lake of Tunis, lake of Ariana, and Sejoumi Lagoon, sustainable water management practices still comprise a concept that has not been implemented. Creating and connecting blue infrastructure might seem far-fetched, but in reality, a few steps at a local scale can set an evolving plan for more complicated and well-established blue infrastructure. With respect to blue infrastructure, this study suggests a blue belt, creating a connection between major (lakes, lagoons, rivers, etc.) and secondary elements that are equally important, such as natural drainage corridors and ponds.

We suggest a few possibilities for green and blue infrastructure maintenance and improvements, starting with the installation of efficient irrigation systems to combat heat waves in the summer and a rainwater harvesting and processing system that can solve two major issues (water scarcity and flooding) simultaneously.

In the future, in order to put an end to the continuous degradation and fragmentation of green spaces, Tunis should consider enhancing and prioritizing the creation of green and blue infrastructure. In addition, key policy recommendations for Tunis should emphasize the need for a holistic and integrated approach to urban planning and management. This includes the development of sustainable and inclusive urban policies while addressing the social and environmental impacts of urbanization. For example, this could include encouraging sustainable consumption and production, managing natural resources sustainably, promoting more balanced regional development based on high-performance, sustainable transportation, improving the quality of life of citizens, and developing energy efficiency.

5. Conclusions

This study provides detailed insights into the patterns, trends, and driving forces of urban growth. A spatiotemporal analysis of urbanization in Tunis from 2000 to 2020 that examined the impact of this growth on green spaces revealed a substantial increase in built-up areas, which was particularly accelerated in the last ten years. Unfortunately, this expansion has led to a reduction in green spaces, which is especially notable between 2000 and 2010.

The expansion of Tunis' urban areas has severely torn apart the layout of green infrastructure and rendered it fragmented, disorderly, singular, and fragile. Moreover, it poses a serious threat and hidden danger to the healthy and sustainable development of the city. Based on the results above, we have constructed a sustainable green space network with blue and green infrastructure interweaved for the city of Tunis, with the hope of providing references and suggestions for the construction of better Tunisian cities or cities facing similar problems and related research.

Our results indicate that the methodological approach utilizing spatial–temporal analysis proves to be valuable in encapsulating the nuances of urban and green space dynamics. This method enables a wide-ranging understanding of the challenges caused by rapid urban expansion. Nonetheless, possible limitations remain with respect to the ability to deal with the qualitative aspects of green spaces fully. In the future, with the advancement of technology, it will be easier to use high-definition satellite images for image interpretation.

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