Spatial Green Space Assessment in Suburbia: Implications for Urban Development

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ABSTRACT

Nonthaburi, a suburban province adjacent to the Bangkok Metropolis, has experienced a reduction in green spaces due to urban expansion. This study quantified Nonthaburi's green space through visual interpretation of land use and land cover (LULC) using THEOS and Sentinel-2. Areas of green space were extracted using remote sensing indices and pixel-based classification based on THEOS. The extracted green area was then integrated with the existing LULC patterns to align with the green space characteristic established by Thailand's Office of Natural Resource and Environmental Policy and Planning. This includes public services, functional utility, median strips, community economics, fallow, and natural green space. The analysis of green space management and planning utilized the Urban Green Space Index (UGSI), Per Capita Green Space (PCGS), and accessibility to public green space. The results revealed that Nonthaburi comprises a green space area of 465.29 km^2 or 73.06%, exhibiting a higher prevalence within its western region while displaying a relatively lower extent in the urban zone adjacent to the Bangkok Metropolis. The per capita green space is 367.71 m^2 but decreases to 255.82 m^2 when accounting for the latent population, meaning it still meets the World Health Organization (WHO) criteria. Currently, only six parks (single and clusters) meet the criteria for public green space. Additionally, both fallow and median strip green spaces (at road interchanges) need to be considered for their potential use in new public service. Furthermore, very high-resolution imagery from unmanned aerial vehicles (UAVs) should be used for green space planning by the organization.

1. INTRODUCTION

Green space refers to any open piece of land that is partly or completely covered with vegetation, such as grass, trees, shrubs, or other vegetation (Lachowycz and Jones, 2013; US EPA, 2017). In both urban and rural environments, green space includes woodlands, parks, gardens, grassy areas, cemeteries, allotments, golf courses, and green corridors such as paths, empty railway lines, rivers, and canals (Carbó-Ramírez and Zuria, 2011; White et al., 2013; Petersen, 2013). Urban green spaces provide a wide range of ecosystem services for city residents (Bastian et al., 2012; Pinto et al., 2022). They serve as settings that promote mental and physical health for all the people living in an urban community. Additionally, they contribute to the maintenance and protection of urban biodiversity, reduce and regulate environmental hazards such as air, water and noise pollution, and mitigate the impacts of extreme weather events (Haq, 2011; Heinze, 2011; Krisdianto et al., 2012; WHO Regional Office for Europe, 2017).

According to guidelines intended to drive sustainable green space management in Thailand, green space refers to natural or human-made areas in cities or communities covered with vegetation as a primary component. It benefits the environment,

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sustains ecosystems, and enhances people's quality of life (ONEP, 2019). This concept is similar to the definition for "vegetated areas" used in most papers according to the terminology and definition reviewed by Taylor and Hochuli (2017). The Office of Natural Resource and Environmental Policy and Planning (ONEP) (2019) established a classification scheme based on utilization patterns divided into six categories as follows: 1) public service with green space such as parks, botanical gardens, playgrounds, and sports fields; 2) functional utility green space such as personal areas, institutional areas, and utility areas; 3) strip green space such as roads, railways and street isles; 4) community economic green space such as paddy fields, field crops, and orchards; 5) natural green space such as wetlands, and bodies of water; and 6) fallow green space such as abandoned land. This coincides with the two different interpretations of green space including green space as nature and green space as urban vegetated space (Taylor and Hochuli, 2017).

The standard for per capita green space is set at a minimum of 9 m^2 per individual (Deloya, 1993; Kuchelmeister, 1998; WHO, 2010; WHO, 2012). The ONEP (2017) suggests that urban communities in Thailand should provide at least 20,000 m^2 of public service green space serving, a minimum of 2,000 people and ensuring not less than 5 m^2 per individual. Further, these spaces should be easily accessible or walkable within a 500 m distance. The ONEP (2019) also suggests that public service green space should not be less than 15 m^2 per individual. The overall green space type coverage for small, medium, and large communities is 25%, 20%, and 15%, respectively.

Due to various factors including mass communication, residential investment, commuting, and infrastructure services, urban growth is affected (Lu et al., 2013). Therefore, urban green space planning is important and necessary. Approaches suggested for urban policymakers and practitioners include clarifying the targets and objectives of green space planning, considering the urban/local planning context and frameworks, adopting a long-term perspective while remaining flexible, and viewing green space projects as investments in public health and social well-being (WHO Regional Office for Europe, 2017). The Twelfth National Economic and Social Development Plan (2017-2021), under the strategic development of urban and metropolitan areas, specifically aims to increase urban green space for recreation and air pollution control services (NESDC, 2017). Abandoned green spaces have the potential to be transformed into public-service green spaces for recreation (Park and Guldmann, 2020). Furthermore, the Twentieth National Strategy proposes that Thailand should consist of green space covering approximately 55% of the total area of the country, with 5% located in urban and rural communities.

Studies tend to focus on general green space extraction using medium-resolution satellite data and overlook the classification of green space patterns by integrating remote sensing techniques, especially in the Southeast Asia region (Richards et al., 2017; Nor et al., 2021). Although some studies incorporate high-resolution satellite imagery for green space pattern classification and planning, they often fail to address the issue of green space accessibility, particularly concerning public service green spaces that can be directly utilized by people. Furthermore, most studies concentrate predominantly on urban and metropolitan areas (Senanayake et al., 2013; Shekhar and Aryal, 2019; Chinnabut et al., 2021; Wirayuda et al., 2023), thereby neglecting the suburban areas that are undergoing urbanization and will be significantly impacted by future urban expansion.

Nonthaburi is one of the central provinces of Thailand and is experiencing high levels of expansion due to its proximity to the extended Bangkok metropolitan region (EBMR) (Kalawong et al., 2018; Nathalang, 2019). This situation is similar to that of another location in Southeast Asia (Xu et al., 2019; Zhao et al., 2020). Consequently, Nonthaburi is facing a complex range of problems arising from a development perspective. The main issues include inadequate waste and wastewater treatment, air pollution, particularly the expansion and distribution of PM2.5, severe traffic congestion and accidents, and the destruction of green spaces (Nonthaburi Provincial Office, 2019).

The Five-Year Nonthaburi Development Plan (2018-2022) proposes the provision of 5 m^2 of urban green space per individual and 30-50% of the total area of government, academic, and religious places designated as environmental green space. Nonetheless, the spatially explicit assessment of the current green space pattern, its quantity, and its compliance with predefined criteria remains an ongoing inquiry essential for effective management and planning purposes. Thus, the objective is to investigate the current state of green space in Nonthaburi, utilizing geoinformatics technologies such as remote sensing (RS) and geographic information systems (GIS). These valuable tools can support and implement appropriate management strategies in this investigation.

2. METHODOLOGY

2.1 Study area

Nonthaburi is located at latitude 13°47'19.63" N to 14°8'25.14" N and longitude 100°15'44.12" E to 100°34'4.09" E, in the low-lying floodplain of the Chao Phraya River, covering an area of 636.82 km^2. It is one of the provinces neighboring the Bangkok Metropolitan area and is divided into two parts by the Chao Phraya River. Nonthaburi consists of six districts and 22 municipalities (Figure 1). The climate in the region is influenced by the north-east and south-west monsoons. The soil texture is predominantly clay and silty clay. Due to the high soil fertility, a significant portion of the area has been utilized for agricultural activities. The registered population in 2019 was 1,265,387 (Department of Provincial Administration, 2019) and the latent population was 553,457 (Nonthaburi Provincial Statistical Office, 2020).

Nonthaburi administrative boundary

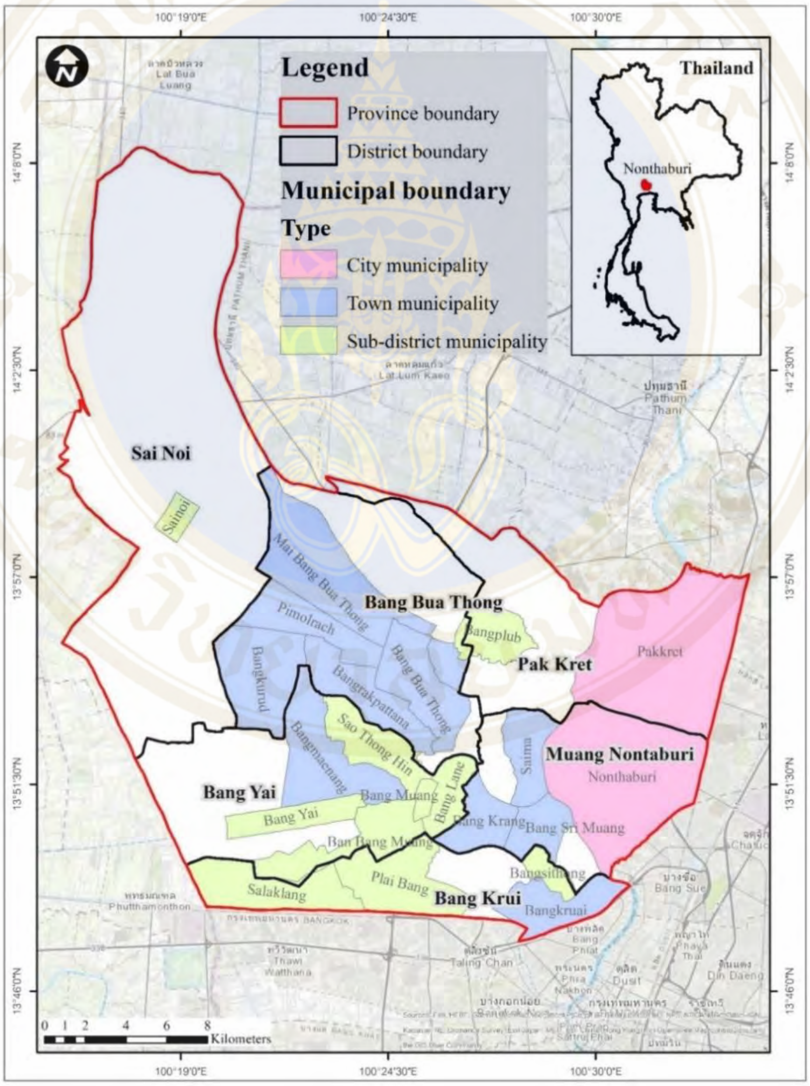

Figure 1. Location of the study site and the province and municipality boundary of Nonthaburi Province, Thailand

2.2 Material and methods

The methodology consists of three major phases (Figure 2) using ArcGIS (ESRI, Redlands, CA, USA) and Sentinel Application Platform (SNAP) (European Space Agency: ESA) software. Firstly, THEOS and Sentinel-2 satellite imagery were processed. Next, land use and land cover (LULC) were interpreted visually. Finally, green space classification and further analysis were conducted using auxiliary data such as road networks obtained from the Ministry of Transportation of Thailand, and public area data derived from Google Maps and NOSTRA Maps. Several indices were applied to highlight critical green space coverage for proposed management planning.

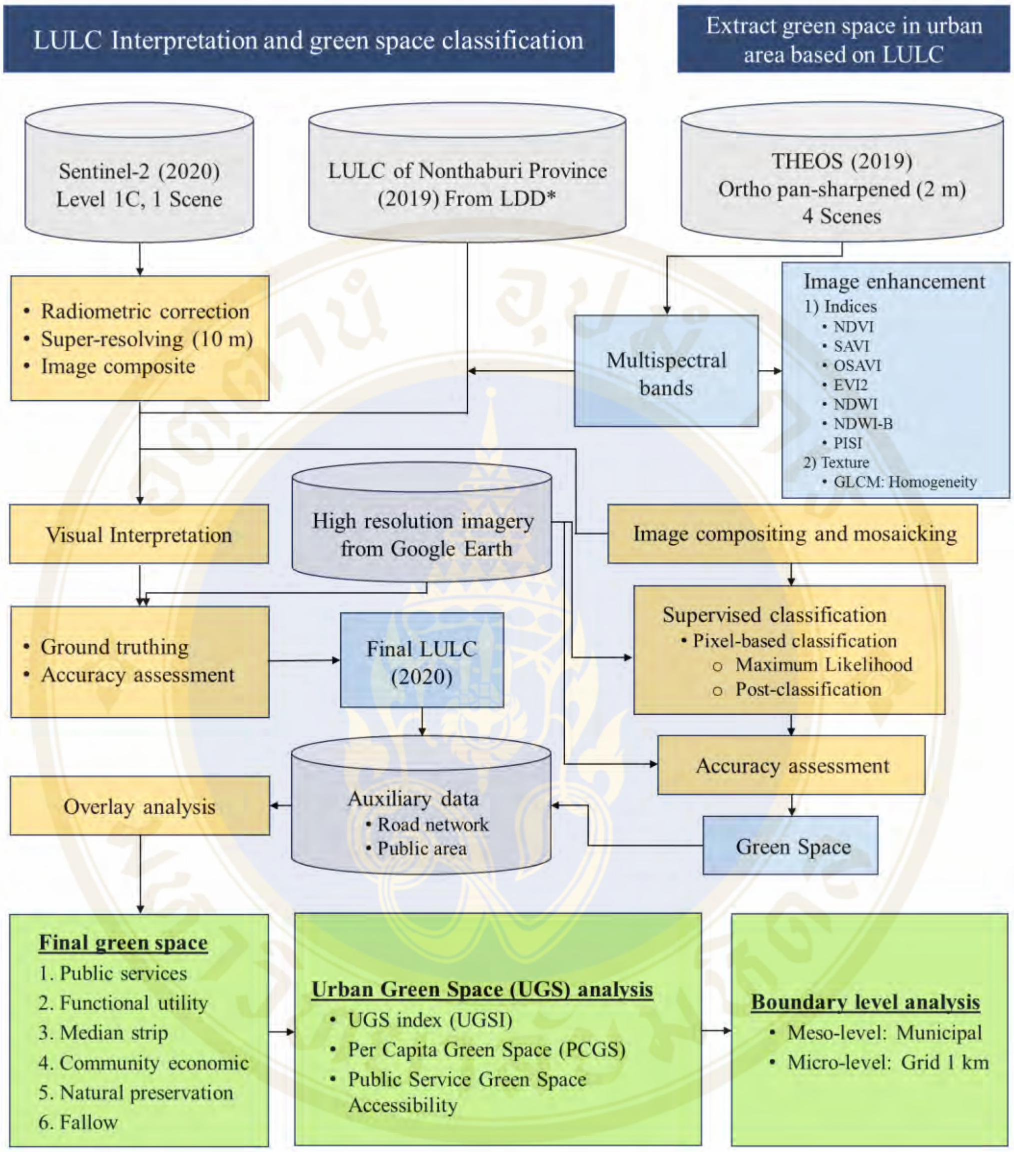

Figure 2. Overall methodology workflow [*LDD=Land Development Department of Thailand]

2.2.1 Satellite data processing

The pan-sharpened THEOS ortho imagery, consisting of four scenes, supported by the Geo-Informatics and Space Technology Development Agency of Thailand (GISTDA), was acquired in May and July 2019. These images had already undergone radiometric and geometric corrections, including ortho-rectification using a digital elevation model (DEM).

The Sentinel-2 imagery, acquired in January 2020, was obtained from the European Space Agency (ESA) Copernicus Open Access Hub. The digital numbers were then converted to top-of-atmosphere reflectance using quantification values proposed by the ESA (ESA, 2015). Additionally, a super-resolving multiresolution with band-independent geometry of multispectral pixels method (Brodu, 2017) was applied to enhance the spatial resolution of all spectral bands up to 10 m. compensating for the lack of a panchromatic band compared to THEOS.

The pan-sharpened multispectral image with its high spatial resolution, allows for the use of automated classification approaches (Sangpradid and Sarapirome, 2014; Abutaleb et al., 2021; Vigneshwaran and Kumar, 2021; Alcaras et al., 2022). Thus, spectral enhancement using pan-sharpened

THEOS data was applied with multi-index models representing vegetation, water, and impervious surfaces, along with grey-level co-occurrence matrix (GLCM) measures of texture to improve classification accuracy (Krefis et al., 2011; Li et al., 2011; Lane et al., 2014). These indices include the Normalized Difference Vegetation Index (NDVI) (Rouse et al., 1973), Soil Adjusted Vegetation Index (SAVI) (Huete, 1988), Optimized Soil-Adjusted Vegetation Index (OSAVI) (Rondeaux et al., 1996), Enhanced Vegetation Index (2-band) (EVI2) (Jiang et al., 2008), Normalized Difference Water Index (NDWI) (McFeeters, 1996), NDWI-B (Qu et al., 2011), Perpendicular Impervious Surface Index (PISI) (Tian et al., 2018), and GLCM homogeneity texture (Haralick et al., 1973) (Table 1).

Table 1. Remotely sensed indices and textural feature used for pan-sharpened THEOS data

Index	Formula	Source
Normalized Difference Vegetation Index (NDVI)	$\frac{NIR - RED}{NIR + RED}$	Rouse et al. (1973)
Soil Adjusted Vegetation Index (SAVI)	$(1 + L) * \left(\frac{NIR - RED}{NIR + RED + L}\right)$ L=0.5 (work well in most situation)	Huete (1988)
Optimized Soil-Adjusted Vegetation Index (OSAVI)	$\frac{NIR - RED}{NIR + RED + 0.16}$	Rondeaux et al. (1996)
Enhanced Vegetation Index (2-band) (EVI2)	$2.5 * \left(\frac{NIR - RED}{NIR + (2.4 * RED) + 1}\right)$	Jiang et al. (2008)
Normalized Difference Water Index ($NDWI_{McFeeters}$)	$\frac{GREEN - NIR}{GREEN + NIR}$	McFeeters (1996)
Normalized Difference Water Index – B (NDWI-B)	$\frac{BLUE - NIR}{BLUE + NIR}$	Qu et al. (2011)
Perpendicular Impervious Surface Index (PISI)	$0.8192 * BLUE - 0.5735 * NIR + 0.0750$	Tian et al. (2018)
Grey-level co-occurrence matrix (GLCM): Homogeneity texture of NIR band with 9 × 9 windows	$\sum_{i=0}^{N-1} * \sum_{j=0}^{N-1} \frac{P(i,j)}{1 + (i - j)^2}$ N denotes the number of gray levels, while P(i, j) is the normalized value of the gray-scale at position i and j	Haralick et al. (1973)

2.2.2 Land use and land cover interpretation

Land use and land cover (LULC) for Nonthaburi in 2019, derived from the Land Development Department of Thailand (LDD), was visually interpreted to create the 2020 LULC. The LULC nomenclature was modified into 13 classes based on the LDD, including paddy fields, field crops and horticulture, perennial and orchard, aquatic plants, aquaculture, urban and built-up areas, roads, recreation areas, golf courses, rangeland and scrub, marshes and swamps, bare land, and water bodies. Subsequently, an intensive ground survey was conducted in April 2020. The sample size was determined using the cumulative binomial probability distribution (Fitpatricks-Lins, 1981) as shown in formula 1.

$$N = \frac{Z^2 pq}{E^2}, Z = 2 \qquad (1)$$

Where; N is the minimum sample size, p is the expected percent accuracy, q = 100 – p, and E is the allowable error. Finally, an accuracy assessment was performed, with an overall accuracy of more than 85% accepted (Congalton and Green, 1999). The Kappa coefficient (Landis and Koch, 1977; Congalton, 1991) was analyzed to generate the final LULC map. The overall accuracy and kappa coefficient were 85.59% and 0.83, respectively (Table S1).

2.2.3 Green space classification and analysis

Since remote spectral indices models are widely used in conjunction with multispectral images and the GLCM measures of texture to improve the accuracy of classified data (Li et al., 2011; Lane et al., 2014; Thakkar et al., 2014; Qu et al., 2021), the extraction of green spaces was performed using a combination of multi-indices models, homogeneity texture, and multispectral images derived from pan-sharpened THEOS data. This was archived through the commonly used pixel-based supervised classification approach known as the maximum likelihood algorithm (ML). Additionally, the spectral indices were rescaled to match the range of the pan-sharpened multispectral images before stacking and using them in the ML algorithm (Lane et al., 2014).

The high-resolution imagery from Google Earth Pro proved to be a powerful resource and was utilized to select the training and verification sites using a grid sampling method (Ghorbanian et al., 2020; Nawar et al., 2022; Adorno et al., 2023; Kruasilp et al., 2023). Subsequently, post-classification analysis was conducted to eliminate the salt and pepper effect from the classified data, followed by an accuracy assessment (Campbell, 1987) (Table S2).

Next, the green space derived from pixel-based classification was overlaid with the LULC data, with particular emphasis on the urban and built-up patterns that fall under the category of functional utility green space. As a result, the final classification of green space was categorized into six classes: public service, functional utility, median strip, community economic, natural, and fallow (Table 2).

Table 2. Typology of green space used in this study

Green space	Land use	Data manipulation
Functional utility	Green area in urban and built-up land, and golf course	Visually interpret urban and built-up and golf course, then extract green space in urban and built-up land using pan-sharpened THEOS based multi-indices model
Public services	Recreation area	Visual interpretation based on Sentinel-2, THEOS, and Google Earth Pro
Median strip	Green area in road island and interchange	
Community economic	Agricultural area	
Natural	Marsh and swamp and water bodies	
Fallow	Rangeland and scrub	

Furthermore, urban green space analysis techniques such as the Urban Green Space Index (UGSI) (formula 2) (Nowak et al., 1996) and Per Capital Green Space (PCGS) (formula 3) were employed to highlight the critical coverage of green space, particularly at the meso-level (municipal area) and micro-level (1 km grid zone) (Alavipanah et al., 2015), which represent the fine-grained distribution of population and economic agglomeration (Jin et al., 2023).

$$UGSI_i = \frac{G_i}{A_i} \times 100 \quad (2)$$

$$PCGS_i = \frac{G_i}{PN_i} \quad (3)$$

Where; G_i=Green space in spatial unit i; A_i=Area of the i spatial unit; PN_i=Population in spatial unit i.

Finally, a proximity analysis was conducted to access walkability to public service green spaces within a 500 m radius (ONEP, 2017; de Sousa Silva, 2018). This analysis was complemented by utilizing the 100 m gridded population count data from 2020 obtained from WorldPop (Bondarenko et al., 2020). The overall workflow is illustrated in Figure 2.

3. RESULTS AND DISCUSSION

3.1 Land use and land cover

Nonthaburi's LULC has been classified visually into 4 major categories with 13 classes based on the nomenclature proposed by the Land Development Department. These classes include: 1) agricultural area (paddy fields (26.91%), field crops and horticulture (5.41%), perennial and orchard (8.13%), aquatic plants (0.85%), and aquaculture (0.68%)); 2) urban area (urban and built-up land (43.94%), roads (1.53%), recreation areas (0.14%), and golf courses (0.10%)); 3) miscellaneous area (rangeland and scrub (2.68%), marsh and swamp (4.54%), and bare land (0.98%)); and 4) water bodies (4.10%) (Figure 3).

3.2 Green space discriminations

The classified LULC, high-resolution satellite images from Google Earth Pro, and intensive ground surveys were used to determine the green space areas based on the definition provided by the ONEP (2019). The total area of classified green space in Nonthaburi Province is approximately 465.29 km^2, which can be categorized as follows: green space for public service (recreation areas) covering about 0.9 km^2, functional utility green space (green areas in urban and built-up land and golf courses) covering about 124.10 km^2, median strip green space (green areas in road islands and interchanges) covering about 0.79 km^2, community economic green space (agricultural areas) covering about 267.41 km^2, natural green space (wetlands and water bodies) covering about 55.01 km^2, and fallow green space (rangeland and scrub) covering about 17.07 km^2 (Figure 4 and Table S3).

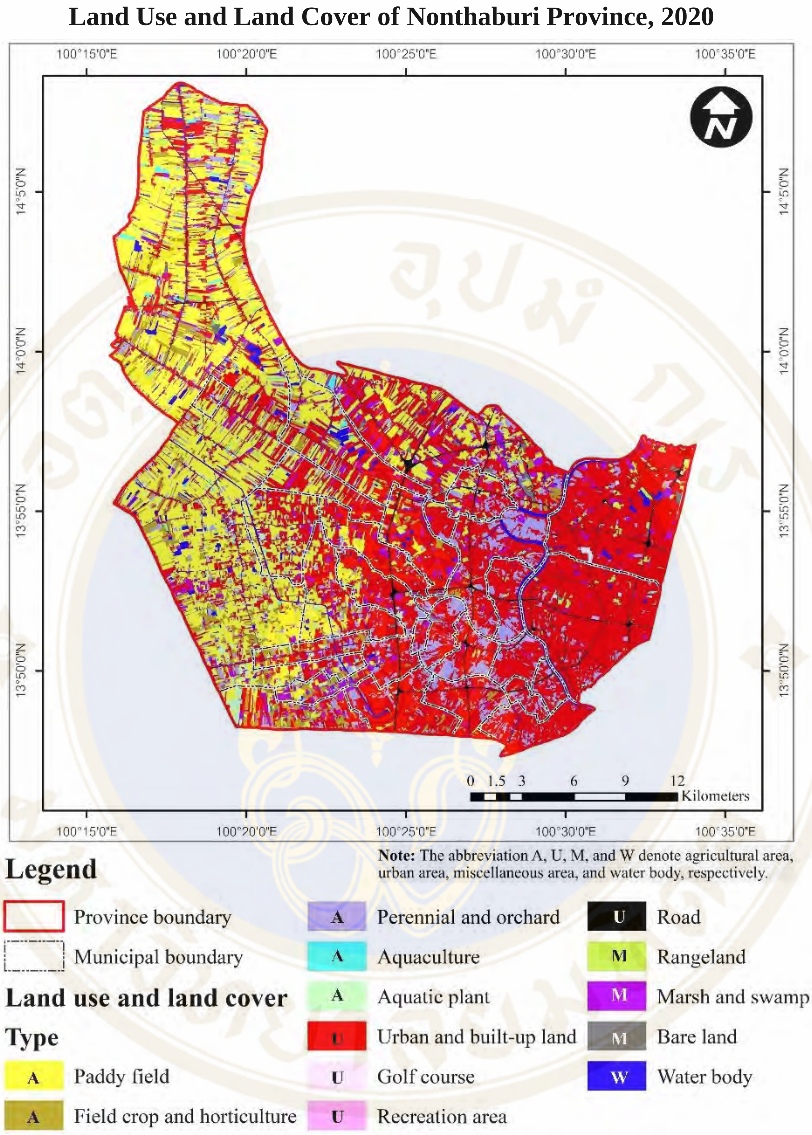

Figure 3. Land use and land cover of Nonthaburi Province, 2020

The Urban Green Space Index (UGSI) in Nonthaburi is 73.06% of the total provincial area. The Per Capita Green Space (PCGS), based on the registered population, is 367.71 m^2 per person. When considering the latent population data, the PCGS decreases to 255.82 m^2 per capita. However, it still exceeds the recommendation by the WHO, which suggests a minimum availability of 9 m^2 of green space per individual with an ideal UGS value of 50 m^2 per capita. Furthermore, it also surpasses the criteria set by the ONEP, which proposes a minimum of 15% UGS for metropolitan cities. Sai Noi district exhibits the highest UGSI and PCGS values of 92.58% and 2,703.24 m^2 per person, respectively, mainly due to the extensive agricultural activities in the area. It also demonstrates the highest UGSI and PCGS values for community economic green space (69.38% and 2,025.96 m^2 per individual), functional utility green space (11.83% and 345.40 m^2 per individual), natural green space (7.68% and 224.27 m^2 per individual), and fallow green space (3.57% and 104.27 m^2 per individual). Conversely, Muang Nonthaburi District, which is predominantly urbanized, has the lowest UGSI and PCGS located values of 44.58% and 89.53 m^2 per individual, respectively (Table S3).

Green Spance Type of Nonthaburi Province, 2020

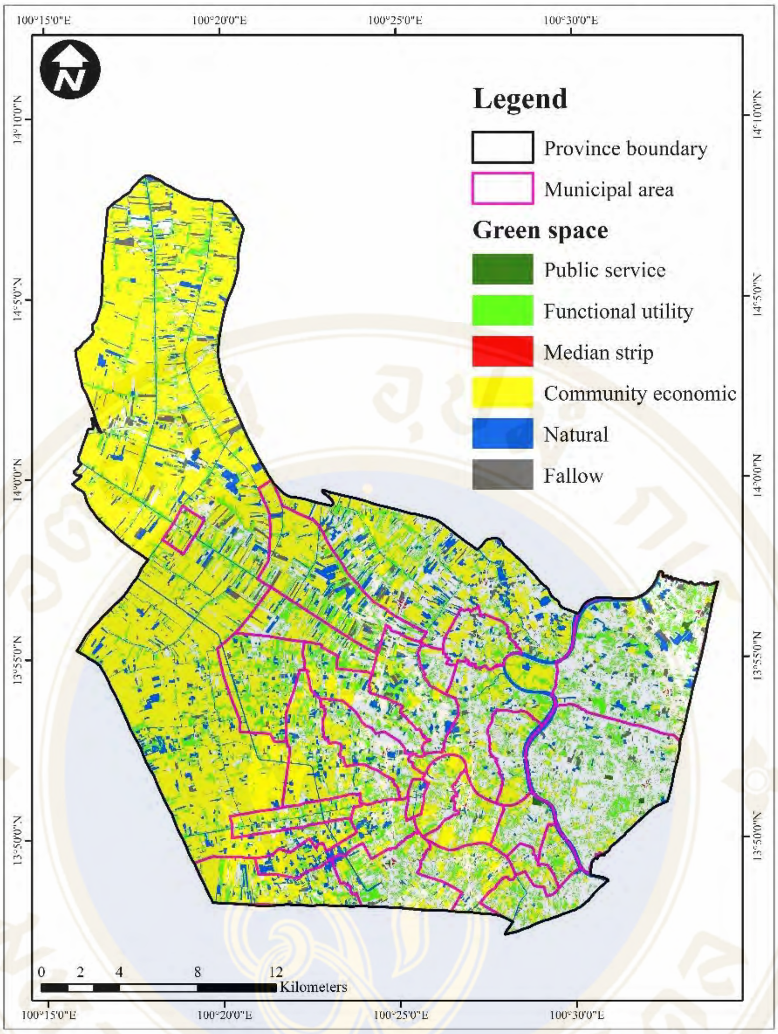

Figure 4. Green space type of Nonthaburi Province, 2020

Urban green space within municipal areas, which depicts the urban characteristics, decreases to 59.31% or 180.29 km^2 compared to the UGSI value of the province. The high UGSI group includes the Bangkurud, Bang Yai, and Salaklang municipalities (85.01%, 82.33%, and 81.92%, respectively). The low UGSI group includes Nonthaburi, Pak Kret, and Bangkruai municipalities (35.22%, 41.22%, and 46.40%, respectively). The high PCGS group includes Sai Noi, Salaklang, and Bang Yai municipalities (844.92, 639.91, and 525.48 m^2 per individual, respectively). The low PCGS group includes Nonthaburi, Pak Kret, and Bang Sri Muang municipalities (57.27, 99.48, and 104.73 m^2 per individual, respectively) (Figure 5). Out of 22 municipalities, 16 consist of green space for public services. Unfortunately, most of them have shown a PCGS lower than the recommended 15 m^2 per individual set by the ONEP (2019) (Tables S4, S5, and S6).

3.3 Grid-based green space

Grid-based analysis was employed to enhance the management approaches for green space. Proposed grids of 1 × 1 km were superimposed with the green space of Nonthaburi. According to the ONEP (2019), the range of green space coverage at the community level should not be less than 15-25%. The results revealed that most of the grids consisted of green space coverage of more than 25%, while 17 grids had less than 25% coverage. These grids were located in Muang Nonthaburi, Pak Kret, and Bang Kruai districts. Significantly, the percentage of green space decreased when adjacent to Bangkok, the capital city of Thailand (Figure 6).

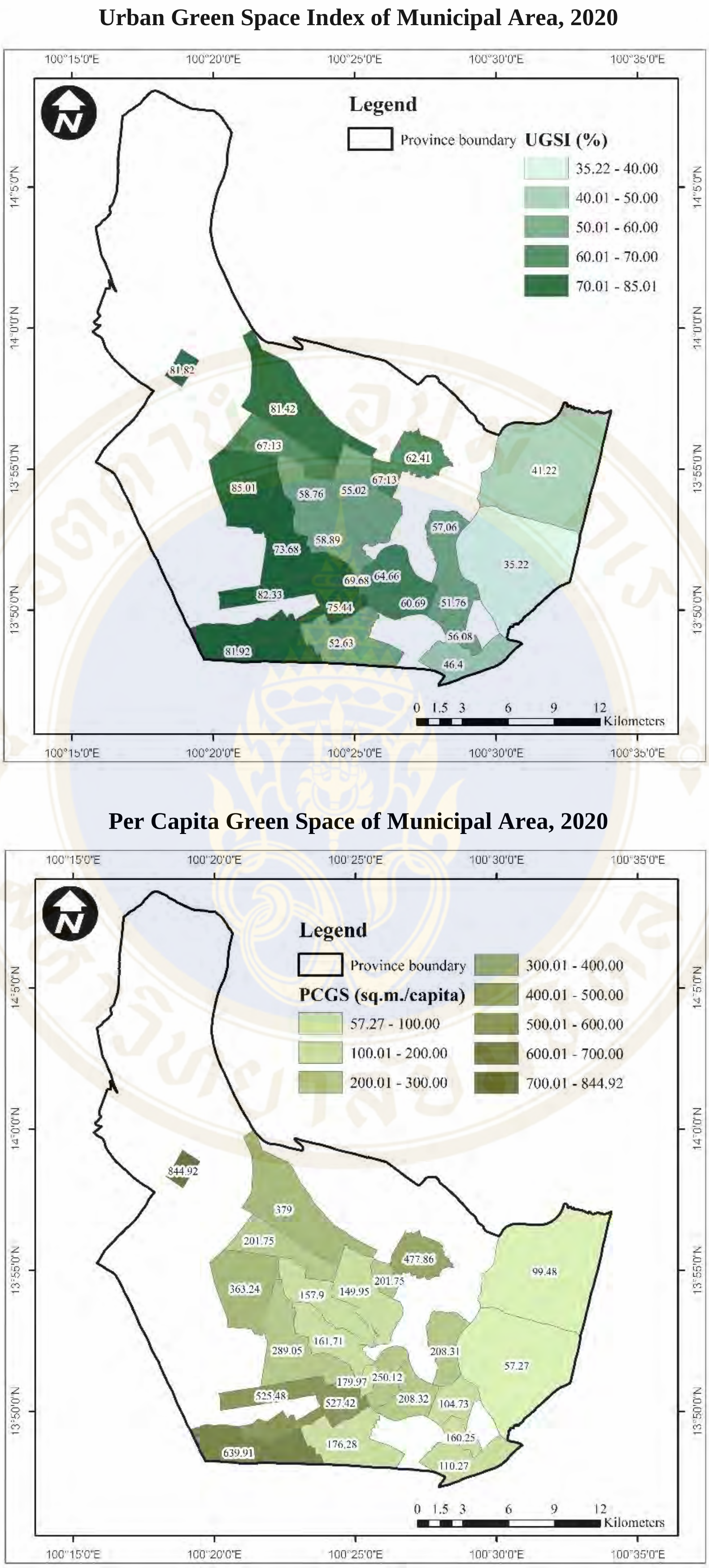

Figure 5. UGSI and PCGS of Nonthaburi municipal area, 2020

Grid Based Green Space of Nonthaburi Province, 2020

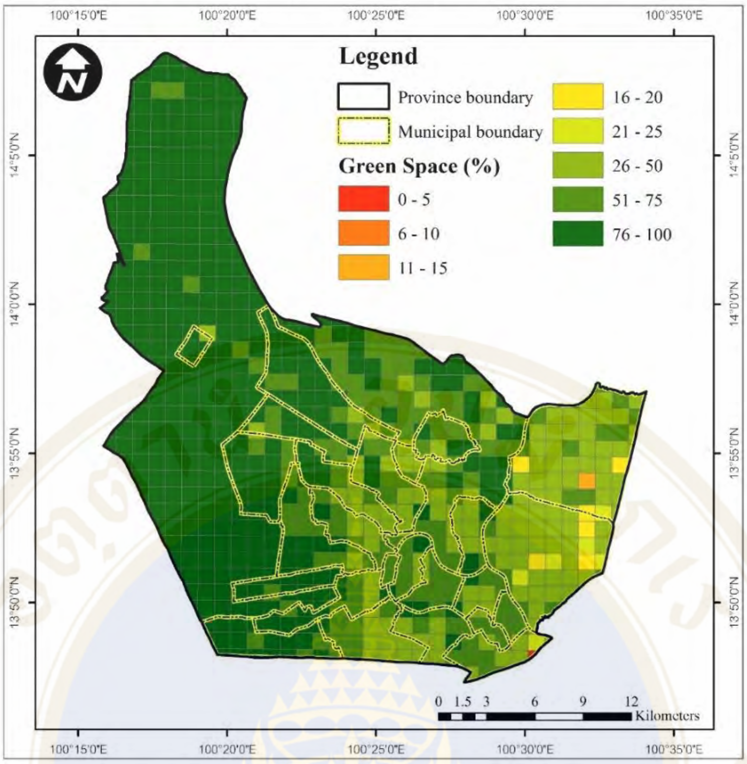

Figure 6. Grid based green space of Nonthaburi Province, 2020

3.4 Public service green space and its accessibility

All of the public service green space can be identified for 41 sites located in Muang Nonthaburi, Bang Yai, Pak Kret, Bang Bua Thong, Sai Noi, and Bang Kruai districts, consisting of 21, 7, 5, 4, 3, and 1 site(s), respectively. Unfortunately, most of them are smaller than 20,000 m^2. However, there are still public services green spaces larger than 20,000 m^2 with a service area of at least 5 m^2 per individual and easy accessibility or walkability within 500 m. These include the Nonthaburi sports stadium, with a total service area of 26,273.35 m^2 and 5.23 m^2 per individual, the park at Bang Khu Wieng interchange, with a total service area of 39,729.17 m^2 and 7.30 m^2 per individual, the park at Chaiyapruek road, with a total service area of 65,382.60 m^2 and 13.01 m^2 per individual, and Somdet Phra Srinagarindra Park, with a total service area of 155,470.01 m^2 and 19.82 m^2 per individual. Although there are parks with green spaces larger than 20,000 m^2, their population density is quite high, resulting in a green service area of less than 5 m^2 per individual. Additionally, some parks located closely within a 500 m range can be grouped as clusters, thus increasing the service area and service per capita, such as the parks at Bang Sri Muang municipality with a total service area of 148,361.12 m^2 and 14.84 m^2 per individual, and the sports field and park in Sai Noi municipality with a total service area of 34,547.31 m^2 and 8.65 m^2 per individual (Figure 7 and Table S7).

3.5 Suitable area for development into public service green space

The abandoned fallow green spaces have the potential to be developed into public service green spaces. Moreover, the green spaces at road interchanges can also serve the same purpose. Thus, these two types of green spaces located in grids with less than 25% green space were chosen. These areas were found within the Nonthaburi and Pak Kret municipalities.

For Nonthaburi municipality, the public service green space would increase from 0.23 km^2 to 0.32 km^2 (a 36% increase) if green spaces at Ngamwongwan interchange and other fallow green spaces were converted (Figures 8 and 9). Meanwhile, the transformation of fallow land in Pak Kret municipality would result in a gain of 25% (0.05 km^2) in the public service green space area.

Furthermore, both potentially fallow and interchange green spaces adjacent to Bangkok also create a new public service green space cluster (the big red 500-m buffer) with increased service area of 0.25 km^2 and 2.06 m^2 per capita (Figure 8).

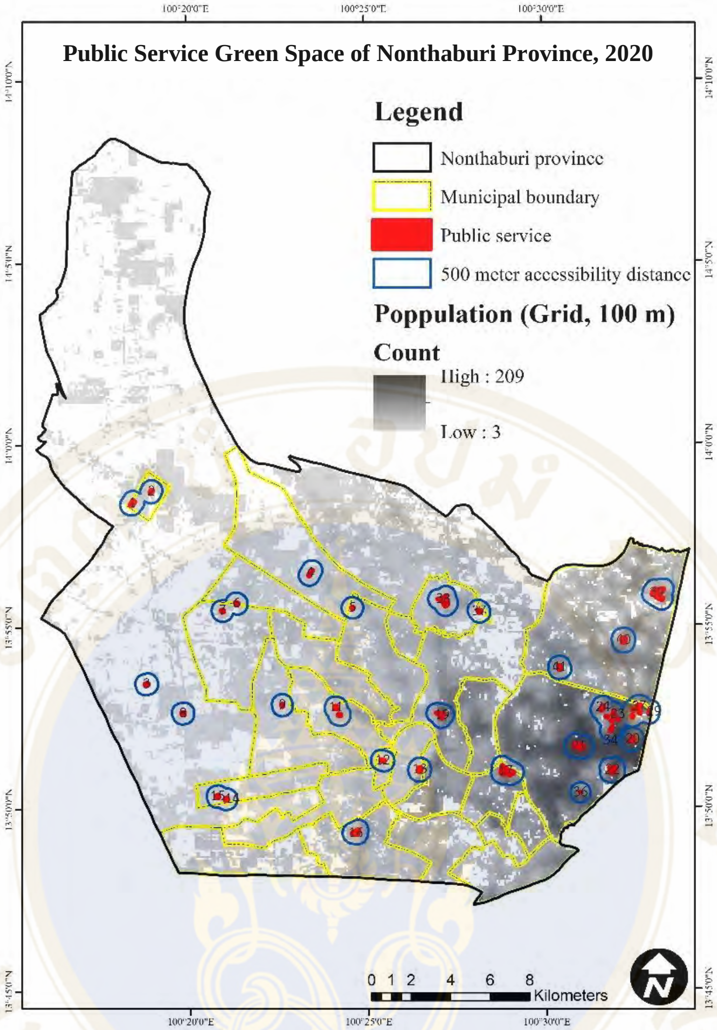

Figure 7. Public green space and accessibility distance of Nonthaburi Province, 2020

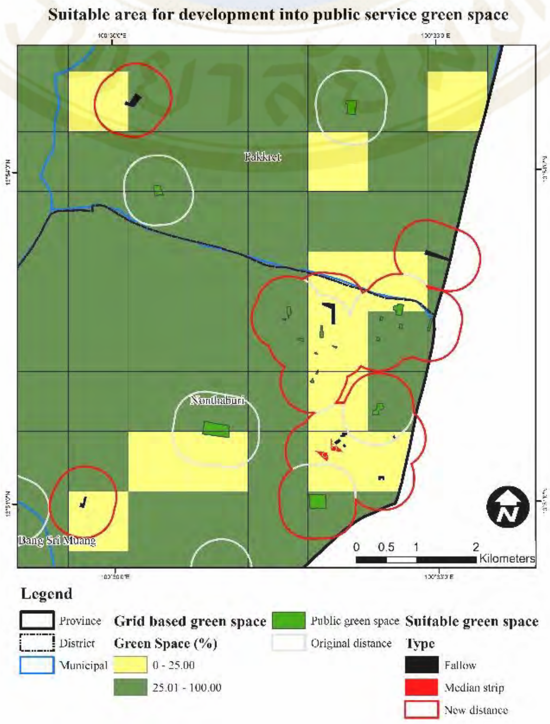

Figure 8. Suitable area for development into public service green space

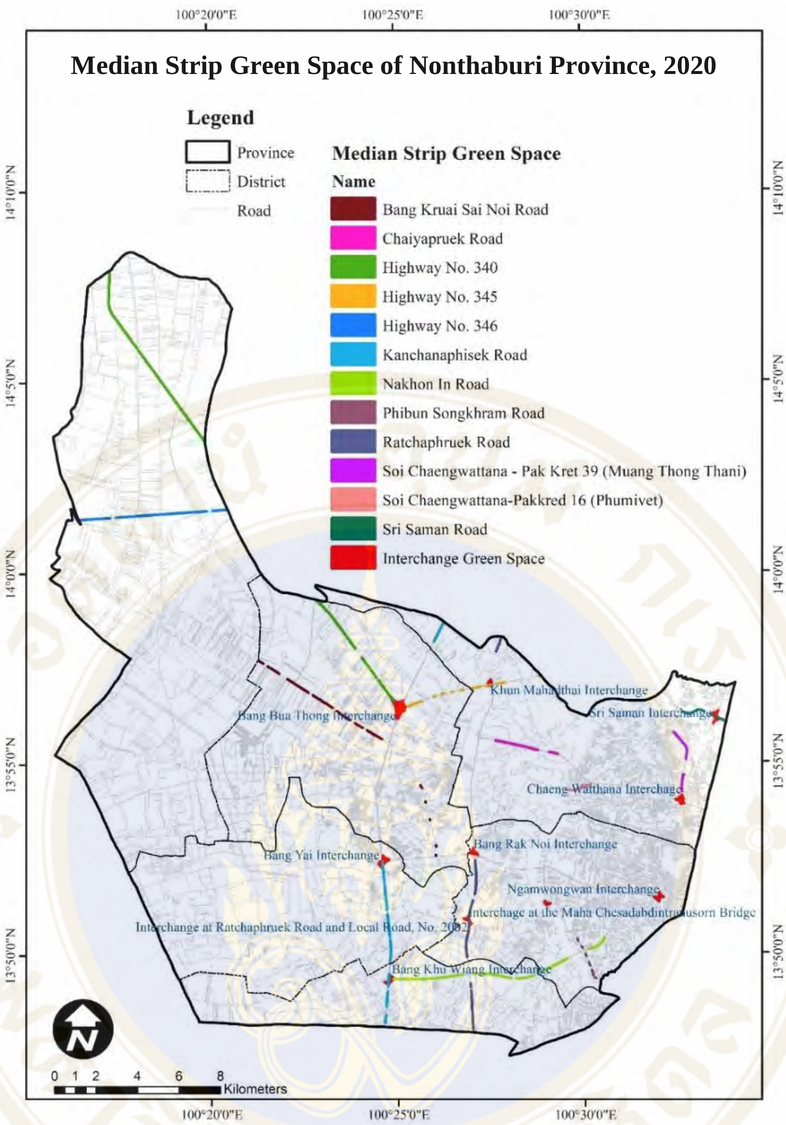

Figure 9. Median strip green space of Nonthaburi Province, 2020

3.6 UAV-based green space

The management of green space within specific locations requires more detailed information to initiate master planning. Higher-resolution data can improve decision-making accuracy. Therefore, UAVs are considered a useful tool to support urban space planning and management. They provide large-scale mapping and a three-dimensional perspective. The Nonthaburi Government Center area was selected for urban green space assessment using UAVs. It was found that green space covers approximately 80,972.30 m^2 or 40.30% of the provincial area (Figure 10). This meets the target set by the Nonthaburi provincial plan (2018-2022), which proposes green space covering about 30-50% of the organization's area.

4. DISCUSSION

This study integrated LULC classification with green space extraction using visual interpretation and computer-assisted classification, along with a multi-indices model, to identify and quantify green space in Nonthaburi Province to support decision-makers in terms of management and planning purposes.

Nonthaburi is identified as having a high-density and mixed-use pattern, similar to other modern compact cities (Russo and Cirella, 2018). Even though there is a significant amount of green space due to agricultural activity in the western part of the province, the UGSI and PCGS tend to decrease as the population increases, particularly in the districts of Muang Nonthaburi, Pak Kret, and Bang Kruai, where the municipalities of Nonthaburi, Pak Kret, and Bang

Kruai are located. The grid-based green space values also align with the UGSI and PCGS. This decrease can be attributed to the development of housing estates in the past, in line with the Fifth National Economic and Social Development Plan (1982-1986) (Sakul-charoenporn and Kiattisahakul, 2021).

Figure 10. Green space in Nonthaburi Government Center, 2020

In terms of spatial distribution, green space in Nonthaburi is similar to cities in other countries, such as Colombo in Sri Lanka and Kalaburagi, and Mumbai in India, where areas located away from the city center tend to have more green space and better environmental quality, while areas closer to the center have less green space (Senanayake et al., 2013; Shekhar and Aryal, 2019; Sathyakumar et al., 2020). This pattern depends on population density, which affects green space coverage, with a higher population in municipal areas such as cities, towns, and sub-districts. However, Nonthaburi municipality differs in terms of urban green space characteristics compared to the municipality of Pattaya, a tourist destination with a UGSI of only 16.57% due to extensive urban and built-up land for tourism purposes (Chinnabut et al., 2021).

Unfortunately, green spaces in Nonthaburi have decreased significantly due to dynamic changes in physical development. The urban and semi-urban areas along the east side of Nonthaburi have experienced significant growth, particularly in the suburbs or urban fringe areas (Nathalang, 2019). Megaprojects for transportation, aimed at linking Nonthaburi with the Bangkok metropolitan area and neighboring provinces, are being developed continuously. These projects include the construction of ring roads, expressways, motorways, and sky trains. Major routes such as the Kanchanaphisek ring road have been expanded to 12 lanes, while Rattanathibeth road has been expanded to 10 lanes. Other development activities that contribute to the reduction of urban green spaces include the expansion of real estate, condominiums, department stores, hotels, and restaurants. Rapid urbanization without retaining adequate green space degrades the urban environment and livability (Song et al., 2021). Moreover, natural disasters such as flooding in 1995 and 2011 have also affected agricultural areas, especially mixed orchards and durian, the most famous fruit and a geographical indicator in Thailand (Thongdara et al., 2013).

According to the Nonthaburi development plan (2018-2022), there are some strategies such as "Developing the area of Nonthaburi Province into a green city, comprising agricultural zones and green urban spaces". Moreover, there are some land use plan zones in Nonthaburi Province's principle city plan in 2023 (Government Gazette, 2023), such as green zone, white zone with green frame and diagonal lines, and light green zone, which represent rural and agricultural land, conservation area for rural and agricultural land, and open space for recreation and maintain environmental quality, respectively. However, the green space may fail to be kept due to gaps in the law regarding land (Chitchang and Cheyklinput, 2022).

Based on the aforementioned, authorities in developing cities should protect environmental resources such as remaining agricultural areas, remnant forest patches, and river corridors. These areas can be re-created as habitats at a later stage of development to maintain urban ecosystem services (Richards et al., 2017). Careful selection of tree species, especially deciduous and dry evergreen species, is important to ensure adaptation to the monsoonal dry season in Thailand, contributing to a more diverse aesthetic quality (Thaiutsa et al., 2008) and effectively mitigating the urban heat island phenomenon (Pan et al., 2023).

The inadequacy of public service green space in Nonthaburi is comparable to other cities that also face uneven distribution and the need for improvement (Oh and Jeong, 2007; Shahfahad et al., 2019; Vîlcea and Şoşea, 2020). As suggested by Park and Guldmann (2020), there is an opportunity to transform neglected fallow green spaces into public service green areas. Furthermore, greater consideration must be given to the development of median strip green spaces at road interchanges as public service green areas. Fortunately, the areas in Nonthaburi addressed in this research are still intact. One particularly promising location is the Ngamwongwan interchange, which is situated in an area with limited green space coverage and requires improvement and development. This is an indispensable component of the city's plan, requiring careful management and planning to ensure its preservation (Suthasupa, 1997). These endeavors play a crucial role in advancing human health and enhancing overall well-being within urban communities, as demonstrated by previous studies (Corley et al., 2021; Pouso et al., 2021; Lin et al., 2023).

Finally, very high-resolution imagery was applied to demonstrate the assessment of green space coverage assessment at a detailed scale, such as the Nonthaburi Government Complex, which requires the use of precise images from UAV sensors (Shahtahmassebi et al., 2021). However, further studies should be conducted using multi-spectral UAV sensors, which can automate classification and integrate with rapid delineation processes.

This study exhibited and emphasized the importance of promoting and enhancing the use of geoinformatics technology in environmental evaluations. Such technology plays a crucial role in achieving the Sustainable Development Goals, specifically SDG 3 (ensuring good health and well-being for all) and SDG 11 (creating sustainable cities and communities).

5. CONCLUSION

This study aimed to identify and quantify green space in Nonthaburi Province using geoinformatics, such as remote sensing and GIS. The green space patterns were modified to align with the nomenclature established by the Office of Natural Resource and Environmental Policy and Planning (ONEP). Due to the prevalence of agricultural land in the rural western areas of Nonthaburi, particularly paddy fields, the green space exhibited a high Urban Green Space Index (UGSI) value for the province. The Per Capita Green Space (PCGS) met the recommendations set by the World Health Organization (WHO). Green space distribution tended to decrease when adjacent to the Bangkok Metropolis. Only six parks or park clusters fulfilled the criteria for public green spaces. The potential for developing fallow green spaces and green spaces at road interchanges into public service areas should be considered. Lastly, the use of unmanned aerial vehicles (UAVs) is suggested for green space assessment at the organizational level.

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DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

APPENDIX A. SUPPLEMENTARY DATA

Supplementary material related to this article can be found starting from Tables S1 to S7.

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