



Temporal Changes in Land Use Dynamics and Mangrove Expansion in the Guandu Wetlands, Taipei, Taiwan

ABSTRACT

Effective conservation of wetlands requires long-term monitoring and evaluation, yet this critical step is often overlooked. This study aims to assess the changes that occurred in the Guandu Wetlands in Taiwan by quantifying land use and land cover between 2007-2018 and 2018-2021. Investigation revealed a total change (including gains, losses, and swaps) of 57.1% from 2007 to 2018, and 32.7% from 2018 to 2021. Notably, the dynamic variations within low-density, medium-density, and high-density mangrove categories were highlighted, with high-density mangroves showing the most significant gains (28.3 and 12.6 %) across both periods. By focusing on preserving and effectively managing the Guandu Wetlands in Taipei, Taiwan, this study serves as a compelling case study that may be applicable to wetlands more widely. The dynamic nature of mangrove ecosystems emphasizes the critical importance of informed conservation and adaptive management strategies. This research contributes to advancing understanding in this field, advocating for proactive measures to safeguard wetland ecosystems.

Keywords: wetlands conservation, land use and land cover, Guandu Wetlands, mangroves, adaptive management strategies

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INTRODUCTION

Mangrove wetlands offer a multitude of benefits, such as: Mangrove wetlands offer a multitude of benefits, such as habitats for wildlife and fishes (Faunce and Serafy 2006), contributing economic value through timber, fisheries, tourism (Malik et al. 2015), serving as carbon sinks (Gu 2022; Taillardat et al. 2018), trapping sediment, facilitating nutrient uptake and transformation, providing a natural barrier against floods and storms, and bolstering the stability of coastal lands against erosion and turbidity (Kandasamy 2021). Unfortunately, wetlands face global challenges, such as degradation and loss of biodiversity, urban development, pollution, and anthropogenic climate change (Chee et al. 2021; Chen and Shih 2019) which have led to the decline and compromise of their ecosystem services. An estimated 54% of the world's mangrove has been lost from 1997 to 2016 (Romañach et al. 2018).

Nevertheless, due to a combination of environmental and anthropogenic factors, such as the introduction of new mangrove species, lack of competitors and predators, and sea level rise, mangroves are expanding in some areas (Chimner et al. 2006; Giri and Long 2016). Cases of mangrove expansion have been recorded in Australia (Williamson et al. 2011), Hawaii (Chimner et al. 2006),

Texas, and Florida (Giri and Long 2016), and Taiwan (Wang et al. 2015).

Previous studies to quantify Land Use and Land Cover (LULC) changes utilized land cover maps or Landsat Data, (Pontius Jr. et al. 2004; Chimner et al. 2006). To understand and monitor these ecosystems, innovative technologies, such as Aerial Photography (Morgan et al. 2010; Giri and Long 2016) and GIS, are important in areas with small ecosystems and fine-scale landscape features; high resolution aerial photographs are useful for the assessment of landscape change (Morgan et al. 2010).

The standard method for calculating the percentage change of LULC categories involves relative difference (Giri and Long 2016). Another common method is the use of a transition matrix for calculating LULC categorical changes over time (Pontius Jr. et al. 2004; Giri and Long 2016). These tools and calculations are useful and direct. However, they did not consider each LULC categorical change interactions between other categories and their respective gains, losses, and swaps (i.e., the exchange of land covers within a specific category between two different time periods) and their persistence rates (i.e., the proportion or percentage of a

specific land cover category that remains unchanged), which is important for understanding the dynamics of LULC transformations. Similarly, achieving desired outcomes is proven difficult due to the challenges associated with monitoring and the absence of systematic evaluation (Meroni *et al.* 2017). Analyzing the dynamics of different LULC can improve the monitoring of the mangrove ecosystem, which has been identified as lacking (Sunkur *et al.* 2024). Monitoring efforts are crucial in assessing the dynamics of mangrove expansion or contraction, providing valuable insights for conservation and management strategies in coastal ecosystems (Sunkur *et al.* 2024).

Mangrove areas in Taiwan covered approximately 400 hectares in 2015 (Chen and Shih 2019). The study was conducted at Guandu Wetlands (**Figure 1**) located in the southwestern part of the Guandu Plain in Taipei, Taiwan about 10 km from the Tamsui River's estuary (Hsu and Lee 2018). It has a total area of 57 ha and it is known to have 300 described bird species, 830 animal species. It is dominated by *Phragmites* and *Kandelia obovata* mangroves species (**Figure 1 and 2**) that are resistant to cold temperatures (Guandu Nature Park 2023; Yang *et al.* 2013). Moreover, *Phragmites* are tall, dense, and competitive due to their ability to thrive in harsh conditions which allows them to dominate by shading and crowding out plants (Rice *et al.* 2000).

Guandu Wetlands has had a previous record of tourist interference, garbage pollution and eutrophication (Chen and Shih 2019). In 1978, due to continuous environmental changes such as accretion, erosion, sand pumping, and land subsidence within the Tamsui River estuary, the landscape in Guandu Wetlands transformed from salt marsh into a mangrove-dominated area. In 1980, the anthropogenic destruction of the mangrove forests of *Kandelia* spp. within the Tamsui River estuary caught public attention and became a turning point in the establishment of the conservation movement in Taiwan. As a result, in 1986, the Guandu Nature Reserve was designated under Taiwan's Culture Heritage Preservation Law to protect the habitat for migratory waterfowl and shorebirds.

After 29 years of the implementation of the Heritage Preservation Law, Taiwan established the Wetland Conservation Act and the Coastal Management Act in 2015, which makes Taiwan at the forefront in wetland protection. This helped in sustainable utilization of wetland ecological services and evaluation to assign an area of "wetland importance" (Su 2014; Chen and Shih 2019). Hence, the Guandu Nature Reserve presents an iconic case to examine how mangroves are expanding

and encroaching into estuary regions.

Therefore, this research aims to comprehensively analyze and document the changes in the Guandu Wetlands over time by utilizing aerial imagery to quantify Land Use Land Cover (LULC) dynamics. Specifically, the study focuses on quantifying the extent of LULC changes between the periods 2007-2018 and 2018-2021, with an emphasis on identifying gains, losses, and swaps within various LULC categories, particularly in mangrove densities.

By enhancing the understanding of wetland dynamics, this study can provide valuable insights for future conservation efforts supporting the development of adaptive management strategies for the effective preservation of the Guandu Wetlands and similar ecosystems. Ultimately in the future, this study may potentially help environmental managers and stakeholders to develop policies that can support conservation efforts of Guandu Wetlands.

MATERIALS AND METHODS

Study Site

The study was conducted at Guandu Wetlands (**Figure 1**) located in the southwestern part of the Guandu Plain in Taipei, Taiwan about 10 km from the Tamsui River's estuary (Hsu and Lee 2018). It has a total area of 57 ha dominated by *Phragmites* and *Kandelia obovata* mangroves species (**Figure 1 and 2**) that are resistant to cold temperatures (Guandu Nature Park 2023; Yang *et al.* 2013). Guandu Wetlands are affected by various factors, including tidal fluctuations, arsenic-contaminated soil, and a homogenous salinity estuary (Yang *et al.* 2013; Liu *et al.* 2013). This area was initially called the Guandu Nature Reserve (Taipei under the Municipal Government) which was established under the Cultural Heritage Preservation Law (CHPL) (Hsu and Lee 2018). Previously, there have been attempts by scientists, government officials and conservationists' managers to restore mangroves dated back to the 1940s (Hsu and Lee 2018). Following the Guandu Wetlands "Nature Reserve" status changed in 2021, no permit was needed to enter the area. Throughout a spatiotemporal scale, the dynamics of Guandu Wetlands have been changing as mangrove areas expand (Hsu and Lee 2018). Overall, the Guandu Wetlands provided an ideal location for the study due to its multi-temporal mangrove coverage, biodiversity, cultural significance, and its previous history of restoration and protection practices.

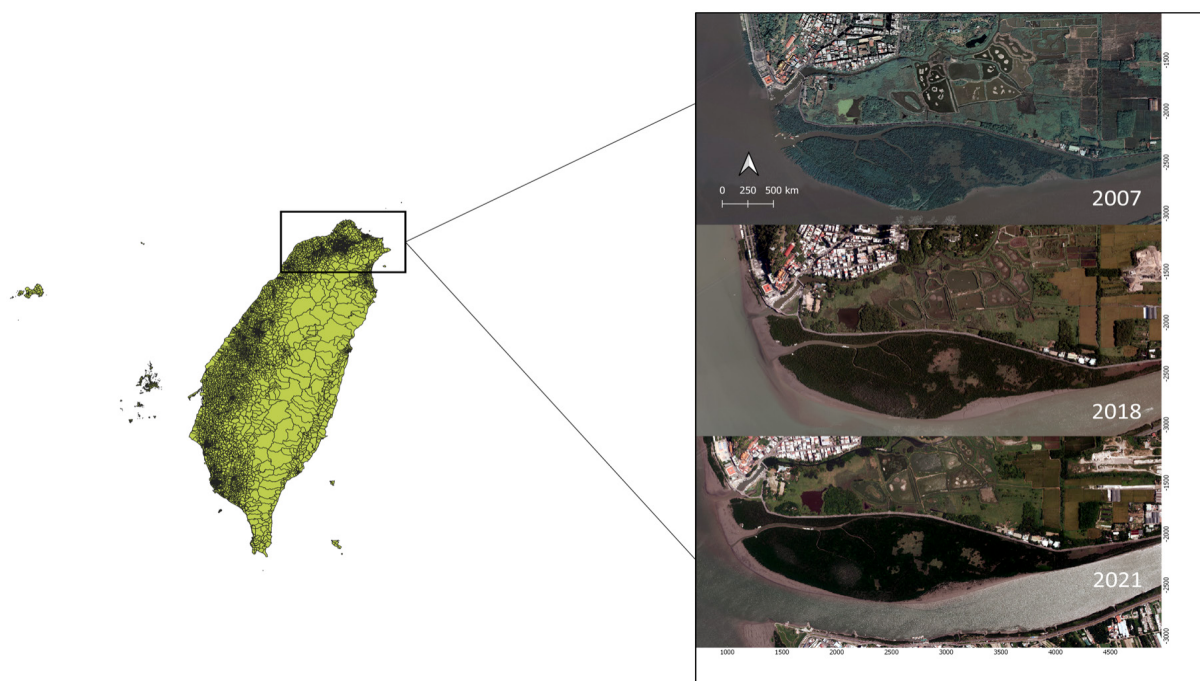


Figure 1. Guandu Wetlands, Taipei, Taiwan. Aerial Images from 2007, 2018, 2021. Coordinates: 121.458718, 25.108917, 121.486183, 25.117767.

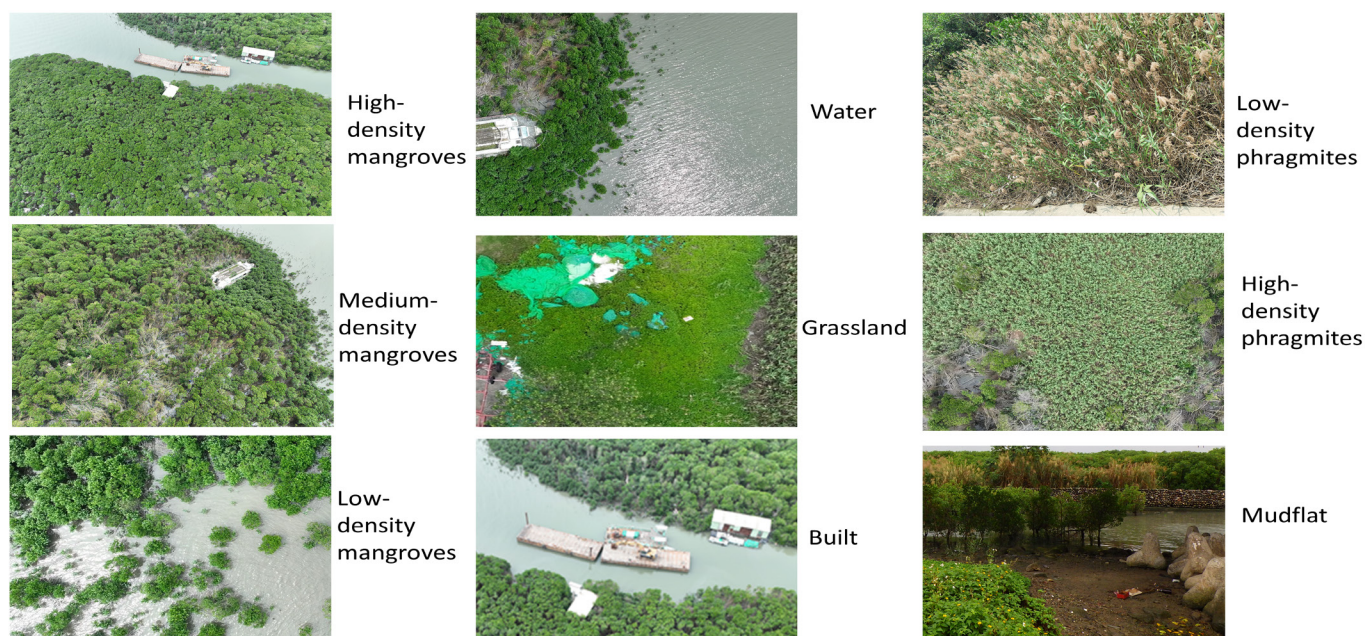


Figure 2. Drone photographs and field photographs of Guandu Wetlands, Taipei, Taiwan during November 22, 2022 and April 13, 2024.

Data Collection and Processing

This study optimized the utilization of aerial photographs in this research to accurately identify LULC categories particularly the mangrove densities. In the study of mangroves, aerial photographs were essential data resource for mapping geographical extent, along with change detection and habitat management. Aerial photographs from the Taiwan Aerial Survey Office provided fine-grain and historical imagery for

detailed change detection. These photographs were rectified into orthophotos with a spatial resolution of 0.25 m, which is essential in identifying the different land types (*Taiwan Aerial Survey Office 2016*). These high-resolution aerial images were taken on October 28, 2007; July 14, 2018; and June 18, 2021 using the digital mapping cameras (DMC and DMC II) and Airborne Digital Sensor (ADS40) (details are available in the *Taiwan Aerial Survey Office 2016*). *García et al. (2016)* proved that using high-resolution aerial images can

accurately help in determining the canopy density. The aerial photographs were processed in ArcMap 10.8.1 and maps are exported into shape and raster file to further analyze the land use land change (LULC) over 2007, 2018 and 2021 (**Figure 3**) (*Public AgriData exchange 2014; ESRI 2011*). The 2007-2018 captured the period when the Wetland Conservation Act and Coastal Management was established (*Chen and Shih 2019*), allowing for an assessment of its impact. Furthermore, 2021 was included in the analysis due to notable changes in wetland status, providing insight into recent developments and management strategies (*Forestry and Nature Conservation Agency 2022*). Using the method of *Hsu and Lee (2018)*, the delineation of mangroves and other vegetation using visual interpretation of aerial images which was completed based on differences in texture, color, location, and tone. This was further confirmed using field validations. Observations were done with binoculars and drone photographs (**Figure 2**).

The accuracy was computed using the method of *Rwanga and Ndambuki (2017)*. Using this approach, this study selected 300 random points on the 2021 map. Since there were nine land types, this study multiplied the total number of points by the ratio of the area of each category to the total area. For this validation, this study used 50 hectares due to limitations in the areas available for drones flying over the Guandu Wetlands. Finally, dividing the total number of correct points by the total number of points and multiplying by 100 yielded an accuracy of 92.67%, indicating high precision.

Data Analysis Using Trend Analysis

Landscape change detection and analysis (*Pontius Jr. et al. 2004*) was used to comprehend the alterations happening in Guandu Wetlands and detect the gain and loss and swap values of the 2007, 2018, 2021. In this study, gain is the increase of a specific LULC Type between two different time periods, while loss is the decrease of a LULC Type over time. Swap indicates the exchange of land cover within a specific category between two time periods, while total swap refers to the overall rate of exchanges between different land cover categories within a landscape over a specific time period. The total change in the landscape corresponds to the combined gains and losses of individual categories. Landscape trend analysis is important for effective wetland management, as it helps identify possible anthropogenic or natural driving forces behind these changes.

This approach focuses on assessing LULC changes across different years to gain a comprehensive

Temporal Changes in Land Use Dynamics

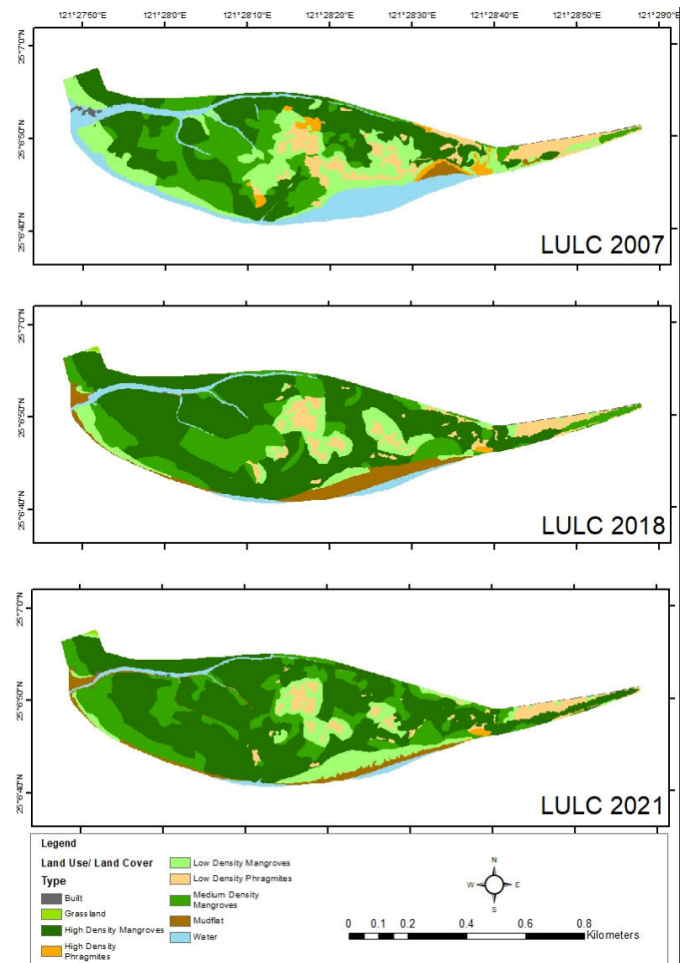


Figure 3. Composition of land types in the Guandu Wetlands, Taiwan for the years 2007, 2018, and 2021. Aerial photographs were used to identify and classify Land Use Land Cover (LULC) categories within the Guandu Wetlands. The LULC categories were manually digitized from the aerial images and represented in raster format.

understanding of the Guandu Wetlands. To perform landscape change detection and analysis, the method by *Pontius Jr. et al. (2004)* was applied by creating a cross-tabulation matrix of the different LULC types. The calculation of LULC changes was based on the equations presented by *Pontius Jr. et al. (2004)*. Gain was determined by comparing the quantity of a specific land cover category in the later map to that in the earlier map. The difference between the two quantities represents the gain for that category. Similarly, loss is computed by comparing the quantity of the land cover category in the later map to the quantity in the earlier map. The difference between these quantities indicates the loss for that category. Swap was calculated by matching areas where there were both gains and losses within a land cover category over time. The swap value was determined as twice the smaller value between the gain

and loss for each category (Pontius Jr. et al. 2004). This method helped identify locations where land cover types were exchanged instead of just gained or lost. To enhance the understanding of Guandu Wetlands changing landscape in 2007, 2018, and 2021, rasters were consolidated using the Combine Spatial Analyst Tool in ArcMap 10.8.1 (ESRI 2011). This process created a composite image that showed the changes in values over these three time periods. This was visualized using the Sankey Diagram with the networkD3 package in R version 4.2.3 (R Core Team 2023, Gandrud 2014). Lastly, the chi-square test (Pearson 1900) was employed to assess the statistical significance of the values for gain, loss, swap, total change, and absolute change during the periods of 2007-2018 and 2018-2021.

RESULTS AND DISCUSSION

Land Use Classification and Species Composition in Guandu Wetland

This study identified nine land types through the aerial images: grassland, low-density mangroves, medium-density mangroves, high-density mangroves, low-density phragmites, high-density phragmites, water, mudflat, and built (Figure 2). The mangrove species were dominated by *Kandelia* genus collectively classified as mangroves. Similarly, all *Phragmites* species were grouped under the *Phragmites* genus. The aerial coverage and percentage of each LULC were for the three periods- 2007, 2018 and 2021 (Table 1).

High-density mangroves dominated in the three years: 2007 (15.48 ha, 31.18%), 2018 (26.18 ha, 52.76%), and 2021 (27.19 ha; 54.78%). The least categories that contributed to the composition were built (0.34 ha; 0.48%) in 2007, high-density phragmites (0.10 ha; 0.21%) in 2018, and grassland (0.04 ha; 0.08%) in 2021 (Table 1; Figure 3).

Analysis of LULC dynamics in the study area revealed significant changes from 2007 to 2018 and from 2018 to 2021 (Table 2). Shifts in various LULC, especially with mangrove densities were observed. In the first time period from 2007 to 2018, Guandu Wetlands exhibited marked changes in LULC especially with the various densities of mangroves. High-density mangroves gained 28.29% while the least amount of area gained was the grassland which is 0.08%. The highest amount of loss was the low-density mangroves (16.27%). Interestingly, it has a slight difference to medium-density mangrove which losses (16.20%). The built category losses were low at only 0.25%.

In the most recent time period, from 2018 to 2021, the LULC dynamics in Guandu Wetlands showed signs of stabilization in certain aspects. It is apparent that the rate of mangrove expansion continued. High-density mangrove had the highest gain of 12.58%. The least category that gained was water (0.05%). Lastly, grassland did not gain any amount of area. The rates of loss in the later time period were lesser compared to the time period of 2007-2018. The high density mangroves had the highest rate of loss (10.56%). The least amount of loss was the grassland category, which was 0.01%. The transition matrix with its respective gains and losses illustrates a continued trend of conversion, albeit an increased mangrove density compared to earlier periods.

Notable swaps and absolute net change were identified; higher swap rates signify dynamic and fluctuating patterns of transition better than different LULC types (Table 3). Absolute net change represents the total amount of change, considering both gains and losses, and provides an overall measure of how much a category has changed. Between 2007 and 2018, the absolute value of net change was 26.84%, and the total swap rate was 30.22%. Notably, the LULC category that fluctuate the most was medium-density mangroves, with

Table 1. Composition of land types in Guandu Wetlands, Taipei, Taiwan in 2007, 2018, and 2021.

Type	2007		2018		2021	
	Area (ha)	Area (%)	Area (ha)	Area (%)	Area (ha)	Area (%)
Grassland	0.00	0.00	0.04	0.08	0.04	0.08
Low-density mangroves	10.55	21.25	5.38	10.85	5.69	11.46
Medium-density mangroves	9.97	20.10	9.11	18.35	10.54	21.24
High-density mangroves	15.48	31.18	26.18	52.76	27.19	54.78
Low-density phragmites	4.17	8.40	3.44	6.93	2.55	5.15
High-density phragmites	1.25	2.52	0.10	0.21	0.17	0.33
Water	7.51	15.13	2.16	4.35	1.42	2.86
Mudflat	0.47	0.94	3.04	6.13	1.88	3.79
Built	0.24	0.48	0.17	0.34	0.16	0.32
Total areas	49.63	100	49.63	100	49.63	100

Table 2. Land Use Land Cover changes of Guandu Wetlands, Taipei, Taiwan with gains and losses in each category, values are in percentages.

		2018										
		Grassland	Low-density mangroves	Medium-density mangroves	High-density mangroves	Low-density phragmites	High-density phragmites	Water	Mudflat	Built	Total 2007	Loss 2007
2	Grassland	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0	Low-density mangroves	0.00	4.98	6.36	9.27	0.55	0.01	0.07	0.02	0.01	21.25	16.27
7	Medium-density mangroves	0.00	0.55	3.90	15.59	0.02	0.00	0.04	0.00	0.00	20.10	16.20
	High-density mangroves	0.08	1.01	5.30	24.47	0.26	0.00	0.06	0.00	0.00	31.18	6.72
	Low-density phragmites	0.00	1.75	0.19	1.43	5.01	0.00	0.00	0.00	0.02	8.40	3.39
	High-density phragmites	0.00	0.35	0.61	0.27	1.09	0.20	0.00	0.00	0.00	2.52	2.32
	Water	0.00	2.16	1.09	1.56	0.00	0.00	4.16	6.07	0.08	15.13	10.97
	Mudflat	0.00	0.01	0.79	0.15	0.00	0.00	0.00	0.00	0.00	0.94	0.94
	Built	0.00	0.05	0.11	0.03	0.00	0.00	0.02	0.04	0.23	0.48	0.25
	Total 2018	0.08	10.85	18.35	52.76	6.93	0.21	4.35	6.13	0.34	100.00	
	Gain	0.08	5.87	14.45	28.29	1.92	0.01	0.19	6.13	0.11		
2021												
2	Grassland	0.08	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.01
0	Low-density mangroves	0.00	5.65	2.19	2.58	0.27	0.00	0.00	0.14	0.01	10.85	5.20
8	Medium-density mangroves	0.00	0.28	8.92	9.13	0.00	0.00	0.01	0.01	0.00	18.35	9.43
	High-density mangroves	0.00	0.71	9.66	42.20	0.08	0.02	0.02	0.07	0.00	52.76	10.56
	Low-density phragmites	0.00	1.46	0.11	0.52	4.75	0.10	0.00	0.00	0.00	6.93	2.18
	High-density phragmites	0.00	0.00	0.00	0.01	0.00	0.19	0.00	0.00	0.00	0.21	0.01
	Water	0.00	0.00	0.14	0.30	0.00	0.00	2.81	1.05	0.05	4.35	1.55
	Mudflat	0.00	3.35	0.20	0.03	0.00	0.02	0.02	2.49	0.01	6.13	3.64
	Built	0.00	0.00	0.03	0.01	0.04	0.00	0.00	0.02	0.24	0.34	0.10
	Total 2021	0.08	11.46	21.24	54.78	5.15	0.33	2.86	3.79	0.32	100.00	
	Gain	0.00	5.81	12.32	12.58	0.40	0.14	0.05	1.30	0.08		

a swap rate of 28.90%. The lowest swap rate was observed in the high-density phragmites, at just 0.01%. From 2018 to 2021, the absolute value of net change was 5.65%, which is lower compared to 2007-2018 at 26.84%. The total swap rate decreased slightly to 27.03% during this period. High-density mangroves exhibited the highest swap rate of 21.12%, while high-density Phragmites again had the lowest swap rate of 0.03%. The gains, losses, total change, swap, and absolute change across the different LULC categories during both 2007-2018 and 2018-2021 were statistically significant (**Table 3**). Chi-square tests revealed extremely low p-values ($p < 0.05$) in both periods indicating that the differences are statistically significant, suggesting that the

distribution of LULC has shifted dramatically (**Table 3**).

Combined raster maps provided visual representation of land cover changes, highlighting the spatial extent and directionality of shifts across the study area. These results were visualized using the Sankey Diagram. These maps, coupled with quantitative analyses, offer valuable insights into localized trends and patterns of land use dynamics, aiding in informed decision-making for land management and conservation efforts (**Figure 3** and **4**).

A large area of high-density mangroves remains stable in the three time periods. Areas with initially medium-density mangroves became high-density mangroves in

Table 3. Summary of changes of Land Use Land Cover in percentage within Guandu Wetlands, Taipei, Taiwan. (2007-2018, 2018-2021).

		Gain	Loss	Total Change	Swap	Absolute Value of Net Change
2007-2018	Grassland	0.08	0.00	0.08	0.00	0.08
	Low-density mangroves	5.87	16.27	22.15	11.75	10.40
	Medium-density mangroves	14.45	16.20	30.65	28.90	1.75
	High-density mangroves	28.29	6.72	35.01	13.44	21.57
	Low-density phragmites	1.92	3.39	5.31	3.84	1.47
	High-density phragmites	0.01	2.32	2.33	0.01	2.31
	Water	0.19	10.97	11.16	0.38	10.78
	Mudflat	6.13	0.94	7.07	1.89	5.19
	Built	0.11	0.25	0.36	0.22	0.14
	Total	57.06	57.06	57.06	30.22	26.84
	Chi-square test ($df=8$)	$X^2=114.10$ $p=2.2 \times 10^{-16}$	$X^2=55.00.1$ $p=4.41 \times 10^{-9}$	$X^2=111.75$ $p=2.21 \times 10^{-16}$	$X^2=114.18$ $p=2.2 \times 10^{-16}$	$X^2=68.20$ $p=1.12 \times 10^{-11}$
2018-2021	Grassland	0.00	0.01	0.01	0.00	0.01
	Low-density mangroves	5.81	5.20	11.00	10.39	0.61
	Medium-density mangroves	12.32	9.43	21.75	18.86	2.89
	High-density mangroves	12.58	10.56	23.14	21.12	2.02
	Low-density phragmites	0.40	2.18	2.58	0.80	1.79
	High-density phragmites	0.14	0.01	0.16	0.03	0.13
	Water	0.05	1.55	1.60	0.11	1.49
	Mudflat	1.30	3.64	4.94	2.60	2.34
	Built	0.08	0.10	0.18	0.16	0.02
	Total	32.68	32.68	32.68	27.03	5.65
	Chi-square test ($df=8$)	$X^2=62.52$ $p=1.49 \times 10^{-10}$	$X^2=35.59$ $p=2.09 \times 10^{-5}$	$X^2=94.811$ $p=2.2 \times 10^{-16}$	$X^2=98.59$ $p=2.2 \times 10^{-16}$	$X^2=7.59$ $p=0.47$

2018 and 2021. Other occurrences low-density mangroves became medium-density mangroves. low-density *Phragmites* only lasted until 2018 and turned into low-density mangroves. Lastly, some cases include high-density mangroves going to medium-density and eventually reverting to high-density mangrove, showing that Guandu Wetland's LULC categories change dynamically.

This study found intriguing patterns in land cover dynamics, emphasizing the significance of medium- and high-density mangroves and the dynamic nature of these ecosystems. Mangroves, among the richest ecosystems in tropical and subtropical regions, require detailed understanding of their temporal and spatial dynamics to predict future trends (Hamilton 2020). Without a detailed understanding, it is possible to

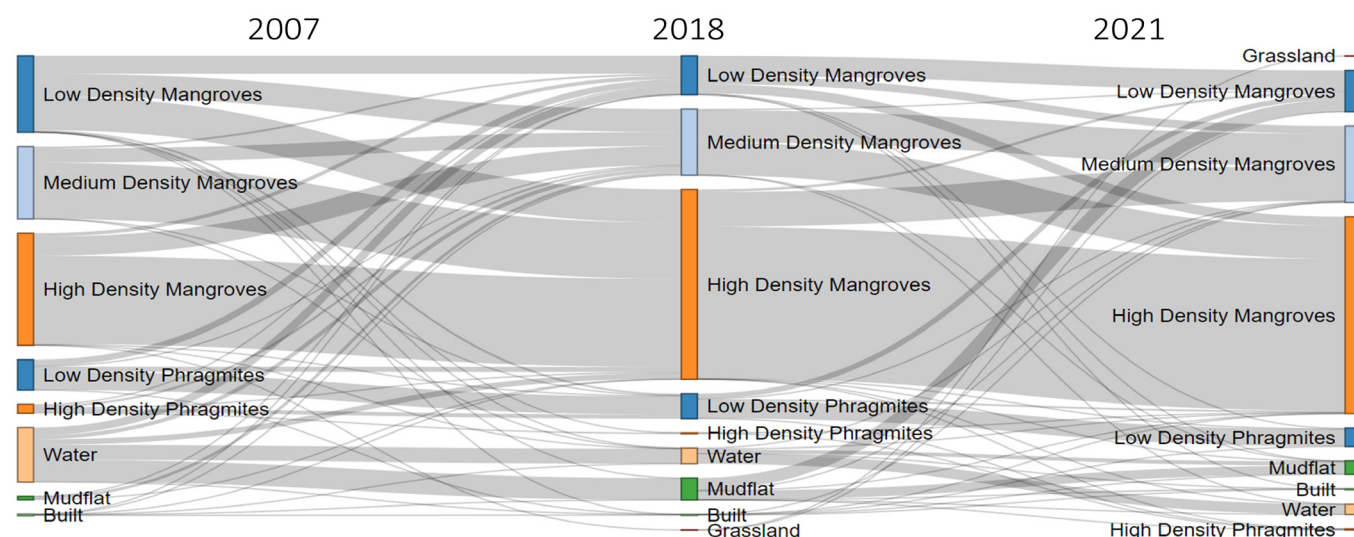


Figure 4. Guandu Wetlands combined raster map of 2007, 2008, 2021 that shows LULC changes. Sankey diagram visualizes the flow and transfers of quantities through 2007, 2018, 2021.

unknowingly underestimate the real dynamics and over simplifying the complexity of land use changes over time. While the previous study from *Hsu and Lee (2018)* have focused on mangroves as a whole, this study's analysis of land types in the Guandu Wetland Areas- a key mangrove wetland in northern Taiwan- revealed significant insights. Increased swap rates signify fluctuating patterns of transition between different land use types, capturing the dynamic nature of landscape transformations, while gains and losses represent an increase or decrease of a specific land use type over time. The absolute net change provides a quantitative measure of the total change in specific land cover categories, irrespective of gains or losses. This study of Guandu Wetlands aids in the identification of patterns of transformation, using historical data from aerial photographs, throughout the landscape and offers insights into the spatial diversity of changes within a category.

Previous study (*Hsu and Lee 2018*) on Guandu Wetlands, showed that mangrove encroachment happens on the *Cyprus*, *Phragmites*, and saltmarshes habitats. The LULC analysis revealed significant shifts between 2007-2018 and 2018-2021, particularly impacting mangrove densities. High-density mangroves had considerable gains in both periods while appearing to remain stable throughout the study periods. Low- and medium-density mangroves had notable losses, reflecting a dynamic interplay between environmental factors and mangrove distribution. Medium-density mangroves exhibited the highest swap rates during both periods, indicating increased mangrove colonization driven by biological and hydrological factors (*Hsu and Lee 2018*, *Willemsen et al. 2016*, *Rice et al. 2000*). Further analysis of combined rasters showed that areas initially classified as medium-density mangroves transitioned to high-density in 2018 and 2021. Other transitions included low-density mangroves evolving into medium- and high-density categories, and low-density *phragmites* from 2018 transforming into low-density mangroves by 2021. Additionally, high-density and low-density *phragmites*, along with mudflats, converted into low- and medium-density mangroves. Despite Water and Built had lower covered areas and few changes. Built categories cannot drastically change due to its nature reserve status. Additionally, due to the geographic location of Guandu Wetlands near the Keelung and Tamsui River, most of the plants are submerged during the high tides and the mudflats appear during low tides (*Forestry and Nature Conservation Agency 2022*).

The decline of *phragmites* may be linked to factors such as bank erosion and mechanical damage (*Crisman*

et al. 2014). Furthermore, some areas of low-density *phragmites* have stabilized within the three time periods (**Figure 4**). *Phragmites* are known to have tolerance to various soil conditions and the ability to invade newly exposed substrates. This herbaceous vegetation often prefers also shallow water and fluctuating levels (*Tulbure and Johnston 2010*).

Furthermore, mangrove plantation began 1978 and good conditions helped its rapid growth. When the nature reserve status was awarded, there were as many as 10 ha of mangrove. Over time and due to the protection status, government authorities and non-government stakeholders did not take any measures to prevent the encroachment of mangroves therefore currently there are about 40 ha of mangrove in Guandu Wetlands (*Forestry and Nature Conservation Agency 2022*).

Several explanations for mangrove expansions might occur as studies have shown that higher elevated intertidal zones are more conducive to the colonization of mangroves and saltmarshes. Therefore, the removal or mitigation of human-made structures that impede tidal exchange and sediment accumulation can promote the establishment of mangroves (*Willemsen et al. 2016*). Mangrove colonization has occurred in different wetlands around the world. For instance, in India, wherein tidal mudflats can potentially provide suitable microenvironments especially during the reduced inflow of freshwater and strong tidal currents that control the estuary and exert an impact on the sediment upstream (*Selvam 2003*). Likewise, instances of mangrove expansion have been documented in Australia; it was observed that there was a 16.2% increase in mangrove presence above the pre-cyclone distribution over the 30-year period (*Williamson et al. 2011*). Despite severe impacts of tropical cyclones on vegetation, mangroves were able to recover which indicates their resilience to cyclone events (*Williamson et al. 2011*). Another case of mangroves colonizing various landforms, including tidal flats, riverbanks, fishponds, canals, protected reefs, embayment, lagoons, and other protected areas were in O'ahu, Hawaii. The percentage increase in mangrove area ranged from 0.32 to 3.24% between different time periods. These numbers reflect the significant expansion of mangroves in O'ahu over several decades, highlighting the rapid growth and spread of these introduced species in Hawaiian coastal environments (*Chimner et al. 2006*). Moreover, expansion was apparent in Texas and Florida with a net increase of 3.8% and 234%, respectively. The research also highlighted fluctuations in mangrove coverage over the years, with the lowest aerial coverage recorded in 1990 and the highest in 2015 (*Giri and Long 2016*).

The inherent biological capacity of mangroves to expand may explain the transition of low-density phragmites into mangrove areas. Since 1978, there has been continuous environmental change triggered by accretion, erosion and sand pumping and land subsidence within the Tamsui river estuary, the landscape in the Guandu Wetlands has transformed from saltmarsh into a mangrove-dominated swamp (Hsu and Lee 2018). The expansion and increase of *Kandelia obovata* in mangrove ecosystems can be attributed to its role as a pioneer species, with the ability to initiate ecological succession processes. Adaptations to the challenging environmental conditions of mangroves, such as high salinity and waterlogged soils, potentially enables *Kandelia obovata* to thrive. The species' fast growth rate facilitates rapid colonization of new areas and out competition of other species, contributing to its expansion. Moreover, its canopy production efficiency in overcrowded stands, characterized by shorter leaf longevity and enhanced resource utilization, further promotes its expansion within mangrove habitats (Sharma et al. 2012). The mangroves are spreading rapidly in the Tamsui River and have a competitive growth advantage due to its proximity to the river. The mangrove invasion is expected to increase due to salt intrusion enhanced by rising sea levels, and riverbed roughness. The expansion of these mangroves is due to the accretion process or abundant allochthonous sediment which enable mangroves to thrive (Williamson et al. 2011). Similar cases have occurred in Sinnarmay estuary in French Guiana, from accretion and mangrove advance, threat and erosion to finally accretion again and mangrove advancing (Fromard et al. 2004). The mangrove area increased in surface area rapidly due to substantial sediment accretion (Fromard et al. 2004). This is also seen in Guandu Wetlands as the as the medium density transitions to high-density but it can also revert to its original category.

Other than ecological and hydrological factors that can explain the expansion and stabilization of the various LULC categories and types, it is also important to note that human impacts that can influence these LULC categories, for instance, urbanization has proven to influence mangrove expansion (Williamson et al. 2011). This can further explain Guandu Wetlands mangrove expansion, since it has been experiencing coastal cementation, sand and gravel collection, river dredging, land subsidence, and urban development (not only in Guandu Wetlands but also in Shezi Islet; *The Society of Wilderness* 2018). During the 2007-2018 period, Taiwan passed the 2015 Wetland Conservation Act, which advocates for biodiversity conservation and sustainable use of wetland ecosystem services and

resources. This act promotes the evaluation of wetlands and assigns priority to their significance. With this said, coupled with the Cultural Heritage Preservation Act of 1986 that designated Guandu Wetlands the highest protection status (Nature Reserve) with the goal to protect important wildlife (Chen and Shih 2019). Consequently, because of this protection status, Guandu Wetlands was not disturbed and it has continued to expand and grow. This study suggests that continued detailed ecological investigations coupled with interviews and group discussions of local residents will provide a clearer picture of potential causes of future changes offer insights into how current land use might evolve following these transitions, which can potentially influence wetland conservation in Taipei City. The dynamic nature of LULC categories in Guandu Wetlands underscores the complexity of landscape changes and the need for continuous monitoring and adaptive management strategies. The results underscore the importance of monitoring and analyzing LULC changes over time to assess environmental trends and inform conservation efforts in the Guandu Wetlands area.

CONCLUSIONS AND RECOMMENDATIONS

The pattern of transitions in Guandu Wetlands, Taipei, Taiwan are characterized by shifts from medium-density to high-density mangroves and back to medium-density, suggests a dynamic response of mangrove ecosystems to environmental changes and management practices. These transitions could be attributed to natural succession processes, as well as potential human interventions, such as restoration efforts, policy changes, and/or changes in land use. Naturally, the *Kandelia* genus is known to be a dominant mangrove species therefore their monitoring is crucial. Understanding these transitions is crucial for informed conservation and restoration strategies, as it reflects the adaptability of mangroves and underscores the importance of continuous monitoring and adaptive management. In the future, monitoring their long-term effects on key wildlife such as waterfowl and shorebirds are important for Guandu Wetlands biodiversity and ecological balance to support these important animals.

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