Multi-Scale Land-Use Change and Vegetation Dynamics in a Tropical Peat Swamp: Implications for Nature-Based Conservation at Wang Krachae, Trat Province, Thailand

Yashodha Herath[1, 2*] and Sakonvan Chawchai[3]

[1]International Program in Hazardous Substance and Environmental Management, College of Interdisciplinary and Integrative Studies, Chulalongkorn University, Bangkok 10330, Thailand
[2]Center of Excellence on Hazardous Substance Management (HSM), Chulalongkorn University, Bangkok 10330, Thailand
[3]Department of Geology, Faculty of Science, Chulalongkorn University, Bangkok 10330, Thailand
**Corresponding Author E-mail: yashodha2lakmali@gmail.com*

ABSTRACT

Tropical peat-swamp ecosystems are increasingly threatened by land-use transformation; however, the vegetation cover can persist even after ecological conversion, making greenness alone an unreliable indicator of ecosystem condition. This study assessed long-term land-use change and vegetation dynamics in the Wang Krachae Peat Swamp, Trat Province, eastern Thailand, using a three-scale framework: the peat-swamp interior, a 2 km surrounding buffer, and the wider sub-district, spanning from 2000 to 2024. We analyzed multi-temporal land-use and land-cover data from Thailand's Land Development Department using post-classification comparison and transition matrices, and used dry-season Landsat imagery to derive the Normalized Difference Vegetation Index (NDVI) for six observation years. Wetlands (Peat Swamp Forest) remained dominant within the interior but declined from 95.41% to 88.81%, while the surrounding buffer and sub-district showed far stronger transformation, with wetland cover falling to 21.13% and 10.36%, respectively, alongside substantial plantation and cropland expansion. NDVI declined sharply between 2005 and 2010 across all scales, most severely within the peat-swamp interior (43.7%), coinciding with extensive transitions to Bare/Degraded Land. Vegetation greenness subsequently recovered by 2024, reaching its highest levels across all three scales. However, this recovery occurred alongside continued localized wetland conversion to plantation, indicating that rising NDVI reflects vegetation regrowth rather than restoration of natural wetland structure and function. These findings show that the peat-swamp interior retains substantial natural cover but faces cumulative pressure from surrounding landscape transformation, pointing toward targeted, nature-based conservation strategies scaled to where pressure is greatest, protecting remaining wetland at the interior's margins, prioritizing the buffer zone where conversion risk is most immediate, and addressing cumulative landscape pressure at the sub-district scale.

Keywords: Land-use conversion/ Normalized Difference Vegetation Index/ Peat-swamp ecosystem/ Remote sensing

1. INTRODUCTION

Tropical peat-swamp ecosystems are among the most carbon-rich terrestrial ecosystems and play an important role in long-term carbon storage and climate regulation. Tropical peatlands are wetlands characterized by waterlogged conditions that inhibit organic matter decomposition, allowing peat and carbon to accumulate and remain preserved for thousands of years [1, 2]. Tropical peatlands are estimated to store 105 Gt of carbon, approximately one-sixth (17%) of the global peatland carbon pool [3]. These ecosystems not only help to regulate the climate but also play a significant role in conserving biodiversity and delivering ecosystem services and resources to the local communities [4]. Hence, their conservation is increasingly considered an important part of strategies to maintain ecosystem resilience under environmental and climatic changes.

Despite their ecological importance, tropical peatlands, particularly those in Southeast Asia, have undergone extensive transformation [5]. The major peat degradation factors in this region are deforestation, drainage, repeated fires, and land-use change to plantations and agriculture [3, 6], with infrastructure development adding another, increasingly relevant pressure. These modifications can

alter vegetation structure, hydrology, peat stability, and ecosystem function [7]. Most importantly, however, vegetation is not always completely eradicated at the time of conversion. Peat swamp vegetation can be replaced with crops or plantations, resulting in a landscape that looks green but undergoes continuous changes in its ecological characteristics and functions.

Assessment of land-use transformation and vegetation dynamics is needed to understand these changes. Appropriate monitoring and management of land-use dynamics are essential for maintaining ecosystem carbon storage and long-term climate stabilization [8, 9, 10, 11]. Remote sensing enables long-term, multi-scale analysis of these processes [12]. The direction and rate of change in the landscape can be detected using land-use and land-cover (LULC) analysis, and the Normalized Difference Vegetation Index (NDVI) is a commonly used indicator of vegetation greenness and temporal vegetation changes [13]. Land-use change also needs to be explored in terms of its spatial context to understand landscape-level pressures on peat swamps. Other pressures involve changes within the wetland and landscape-level pressures from agricultural and plantation development [14]. Previous studies show that land-use conversion and related disturbances have significantly altered the landscape of tropical peatlands in Southeast Asia, primarily through conversion to industrial plantations, artificial drainage, conversion to water bodies and aquaculture (including shrimp farming), and recurrent fire, among other disturbances common across the region [4, 6]. Reviewing Peatland boundaries alone cannot identify important changes in the wider landscape that provide broader context for understanding pressures on the Peatland. The Wang Krachae Peat Swamp in Trat Province, Thailand, is one such case to explore these interactions. The peat swamp lies within a broader area with various land-use categories, including agriculture, plantations, built-up areas, and others. This study is therefore conducted using three scales, namely the peat-swamp interior, a 2 km surrounding buffer, and a wider sub-district scale, to evaluate long-term peat-swamp land-use transformation and vegetation dynamics, which span from 2000 to 2024.

This study aimed to understand spatial and temporal changes in LULC in and around the Wang Krachae Peat Swamp and the vegetation changes associated with land-use change. The Thailand Land Development Department (LDD) provided LULC data, which we classified using multi-temporal classification methods, and we calculated NDVI from Landsat imagery acquired during the dry season for 2000, 2005, 2010, 2015, 2020, and 2024. This study uses multi-scale analysis by synergizing LULC and NDVI trajectories to provide a landscape-level assessment of the response of a tropical peat-swamp landscape to a long-term land-use transformation and to highlight the difference between recovery of vegetation greenness and recovery of natural wetland structure and function, relevant to informing conservation priorities for peat-swamp ecosystems within their surrounding landscape.

2. METHODOLOGY

2.1 Study Area and Multi-Scale Analytical Framework

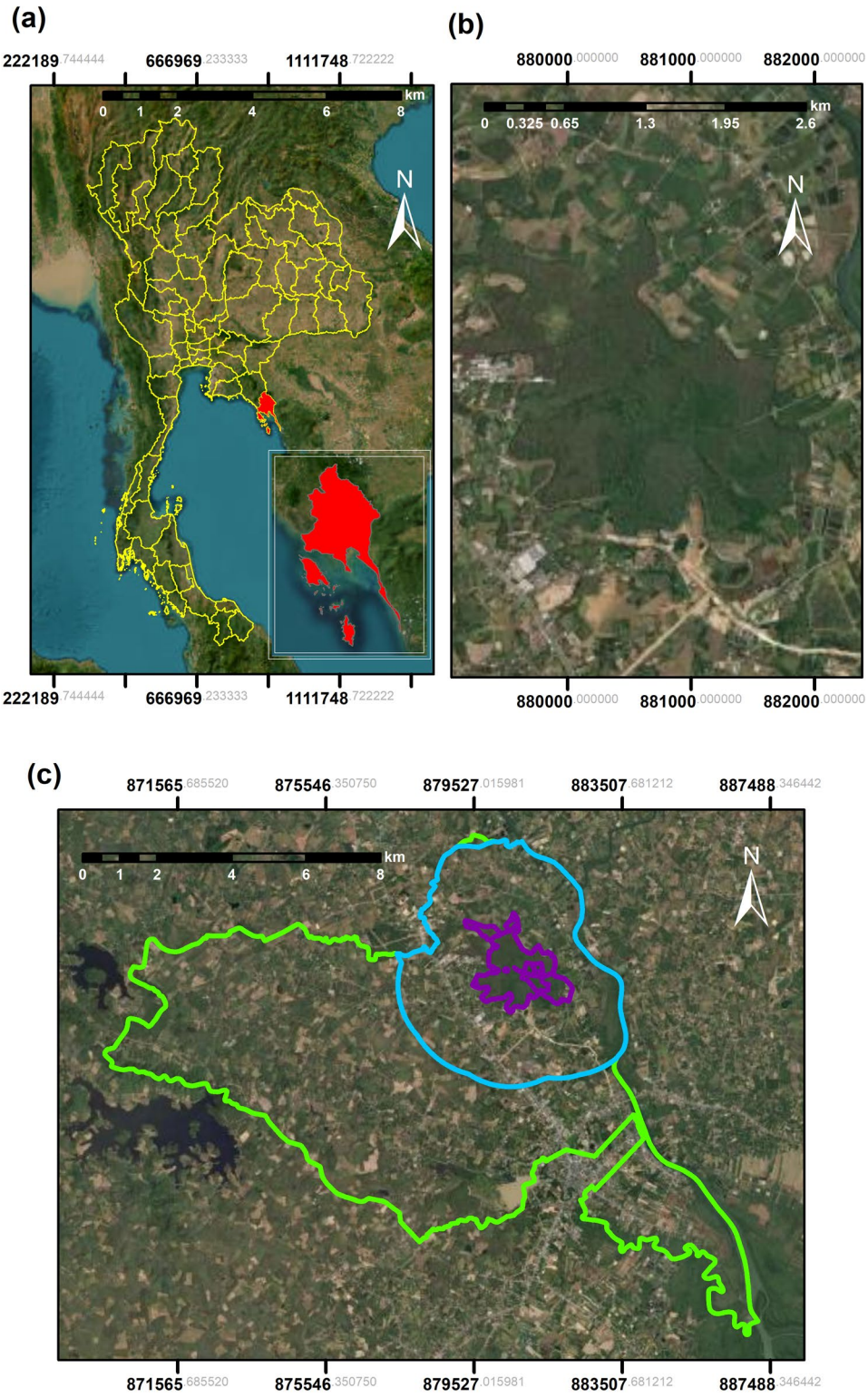
The study was carried out in the tropical peat swamp system of Wang Krachae Peat Swamp (Figure 1a-b), located in Trat Province, Thailand, where the peat swamp is nestled in an agricultural and plantation landscape, about 20 km from the seashore. Wang Krachae is one of the relatively small peatland complexes in eastern Thailand and offers a representative landscape for understanding environmental change.

The peat-swamp interior covers approximately 336.87 ha, delineated from Forest Industry Organization (FIO) spatial data for this study. A larger figure, approximately 7.5 km², has been reported for the wider Wang Krachae site in separate stratigraphic work [15], reflecting a different delineation purpose rather than a discrepancy in the site's actual extent. Like other tropical peat swamp forests, Wang Krachae stores carbon over long timescales through waterlogged, oxygen-poor soils that slow decomposition [1, 2, 3], and its hydrology helps regulate water tables and flow across the surrounding landscape [7]. The FIO stewards it, and it currently serves as a research and plantation site. To distinguish change within the peat-swamp interior from broader landscape influences, three scales of

analysis were set: the peat-swamp interior, a 2-km buffer zone, chosen to be well beyond the range where plantation-related ecological effects have been measured in similar peatland settings up to about 700 m from plantation boundaries [16], and the wider Wang Krachae subdistrict (Figure 1c). The peat-swamp boundary represented the peat-swamp ecosystem interior, the buffer represented the immediate surrounding landscape, and the subdistrict represented the broader landscape context. The 2-km buffer was generated as a uniform radial buffer around the peat-swamp boundary, then clipped to the Wang Krachae subdistrict boundary, consistent with the study's administrative framing; consequently, the buffer's mapped extent follows the subdistrict boundary where the two intersect, rather than mirroring the peat swamp's own outline in full. This multi-scale perspective enabled assessment of both land-use change and vegetation processes within the peat swamp and across the surrounding landscape.

The administrative subdistrict was selected as the outer analytical scale, rather than a hydrologically defined catchment, for consistency with the administrative datasets underlying this study (LDD land-use data, Royal Thai Survey Department boundaries) and because land-use governance in Thailand operates at this administrative level, making results reported at this scale more directly applicable to local land-use management. This choice means the subdistrict boundary does not fully encompass the peat swamp's hydrological catchment, and the upper, non-administratively bounded portion of the surrounding landscape was not included in this analysis; this is acknowledged as a limitation of the spatial design and addressed further in the Discussion.

In this study, the term 'wetland' refers broadly to permanently or seasonally waterlogged ecosystems, while 'peat swamp' refers specifically to the waterlogged forest ecosystem accumulating organic soil and peat at Wang Krachae [15]. The peat-swamp interior refers to the fixed physical boundary of the peatland provided by the FIO, used consistently as the study's interior spatial zone across all six assessment years; this boundary is distinct from the 'Wetlands and Peat Swamp Forest' LULC class, whose mapped extent within the interior zone varies by year as other land-use types occur within the same boundary.



Service Layer Credits: Source: Esri, Maxar, Earthstar Geographics, and the GIS User Community

Figure 1. (a) Location of Wang Krachae (WKC) peat swamp, (b) expanded view of the peat swamp, (c) Multi scale framework for the study area at Wang Krachae; Peat Swamp Zone in purple boundary; Buffer zone in cyan boundary and the administrative sub-district in green boundary.

2.2 Data sources and data collection

Landsat 5 TM and Landsat 8 OLI/TIRS Collection 2 surface-reflectance data were retrieved from Google Earth Engine (GEE) [17]. Dry-season imagery (December–March) was used to reduce seasonal variability and cloud contamination, with a cloud-cover threshold of 50% applied across all scenes, consistent with thresholds commonly used for cloud-frequent tropical regions, where stricter thresholds substantially reduce the availability of usable imagery.

Landsat scenes were first filtered by study-area boundary and this cloud-cover threshold, selecting scenes suitable for compositing. Selected scenes were then preprocessed using per-pixel cloud and cloud-shadow masking, applied via the Landsat Collection 2 QA_PIXEL quality band, and surface reflectance scale factors were applied to convert digital number values to physically meaningful reflectance units. Observations within each year were then composited together by a pixel-wise median composite to reduce the effects of any remaining cloud, shadows, and anomalous pixel values. Supplementary Table 1 provides full acquisition details, including individual scene IDs, acquisition dates, and cloud cover percentages for all Landsat scenes used in each annual composite. Historical Google Earth Pro imagery was used to visually contextualize land-use patterns flagged by the classification, particularly bare/degraded areas and apparent plantation establishment. A single interpreter conducted this interpretation without formal cross-validation; this limitation is addressed in the Discussion.

2.3 LULC Data Harmonization

The detailed LDD classes were harmonized into seven generalized categories: Wetlands and Peat Swamp Forest, Other Natural Forest, Plantation Agriculture, Agriculture/Cropland, Built-up Areas, Water Bodies and Aquaculture, and Bare/Degraded Land, as shown in Table 1. The generalized LULC classification scheme used for multi-temporal land-use change analysis is shown below. This harmonization ensured consistent land-use classification across years while maintaining key land-use differences important to the peat swamp landscape. The harmonized class information was then classified to 30-m resolution raster files based on the polygon codes and spatially registered to facilitate further LULC transition and NDVI integration analyses.

Table 1. Generalized LULC classification scheme used for multi-temporal land-use change analysis

Generalized LULC class	Classification basis
Wetlands and Peat Swamp Forest	Wetland-associated and peat-swamp forest ecosystems
Other Natural Forest	Non-peat natural forest vegetation
Plantation Agriculture	Perennial/commercial plantation systems, predominantly rubber (93.7% of plantation area), with minor oil palm (5.6%), coconut (0.4%), and teak (0.3%)
Agriculture/Cropland	Agricultural and annual cropping systems
Built-up Areas	Residential, urban, infrastructure and other developed surfaces
Water Bodies and Aquaculture	Open water and managed aquatic areas
Bare/Degraded Land	Bare, sparsely vegetated and degraded surfaces

2.4 LULC Change and Transition Analysis

LULC change was assessed separately for the peat-swamp interior, 2 km buffer, and sub-district by calculating the area and percentage of each generalized class for each observation year. Changes in LULC data were identified using post-classification comparison, and transition matrices were created to determine transitions between the seven generalized classes [18]. Classification accuracy of the harmonized seven-class LULC scheme was assessed using stratified random sampling (n = 112 valid points) and standard confusion matrix procedures, achieving an overall accuracy of 88.39% and a Kappa coefficient of 0.856 for the 2024 classification. The study highlighted wetland conversion to plantation, agriculture, built-up areas, and water/aquaculture, as well as transitions to bare/degraded lands.

These transition patterns were then combined with NDVI to investigate vegetation dynamics associated with significant land-use change.

2.5 NDVI Calculation and Spatial-Temporal Analysis

The red and near-infrared (NIR) surface-reflectance bands were used to calculate NDVI as follows:

$$NDVI = \frac{NIR - Red}{NIR + Red}$$

Band 4 (NIR) and Band 3 (Red) of the Thematic Mapper (TM) were selected for Landsat 5 TM, and Band 5 (NIR) and Band 4 (Red) were selected for Landsat 8 OLI. NDVI is a normalized indicator of plant greenness, and it is commonly used to characterize spatial and temporal vegetation dynamics [13]. We then exported the NDVI composites as 30-m GeoTIFFs and analyzed them across the peat-swamp interior, 2 km buffer, and sub-district.

Zonal statistics were calculated to compute mean NDVI at each spatial scale for each observation year, and six temporal observations were used for each spatial scale to assess vegetation trajectories. Spatial changes were determined by comparing NDVI surfaces across observation years, and temporal trends were estimated from mean NDVI values using linear trend analysis. Annual NDVI layers were stacked on the generalized LULC-transition layers, and mean NDVI values were calculated for each LULC-transition category to explore how vegetation responds to land-use change. Special focus was placed on Bare/Degraded Land to the extent that vegetation decreases were associated with a possible disturbance to the land from clearing and recovery in NDVI. The difference in NDVI was measured between observation periods and across the full period 2000-2024. Google Earth Pro historical imagery was also used to provide context for larger land-cover changes, such as bare/degraded areas and apparent plantation establishment.

2.6 Interpretation of Integrated LULC- NDVI

Finally, the three spatial scales of LULC transition patterns and NDVI trajectories were combined and interpreted. The analysis identified whether major land-use changes were followed by shifts in vegetation greenness, and whether NDVI recovery resulted from restoration of natural wetland vegetation or a new type of alternative vegetated land use. The study emphasized the correlation between wetland conversion, bare/degraded land, plantation development, and NDVI trajectories. This enabled the study to identify decreases in vegetation greenness due to land clearing or disturbance, and the greening-up that occurred as vegetation regrew. The integrated interpretation thus focused on NDVI as an index of vegetation greenness, rather than an indicator of natural ecosystem integrity, because different vegetation types can have similar NDVI [13]. The workflow is shown in Figure 2.

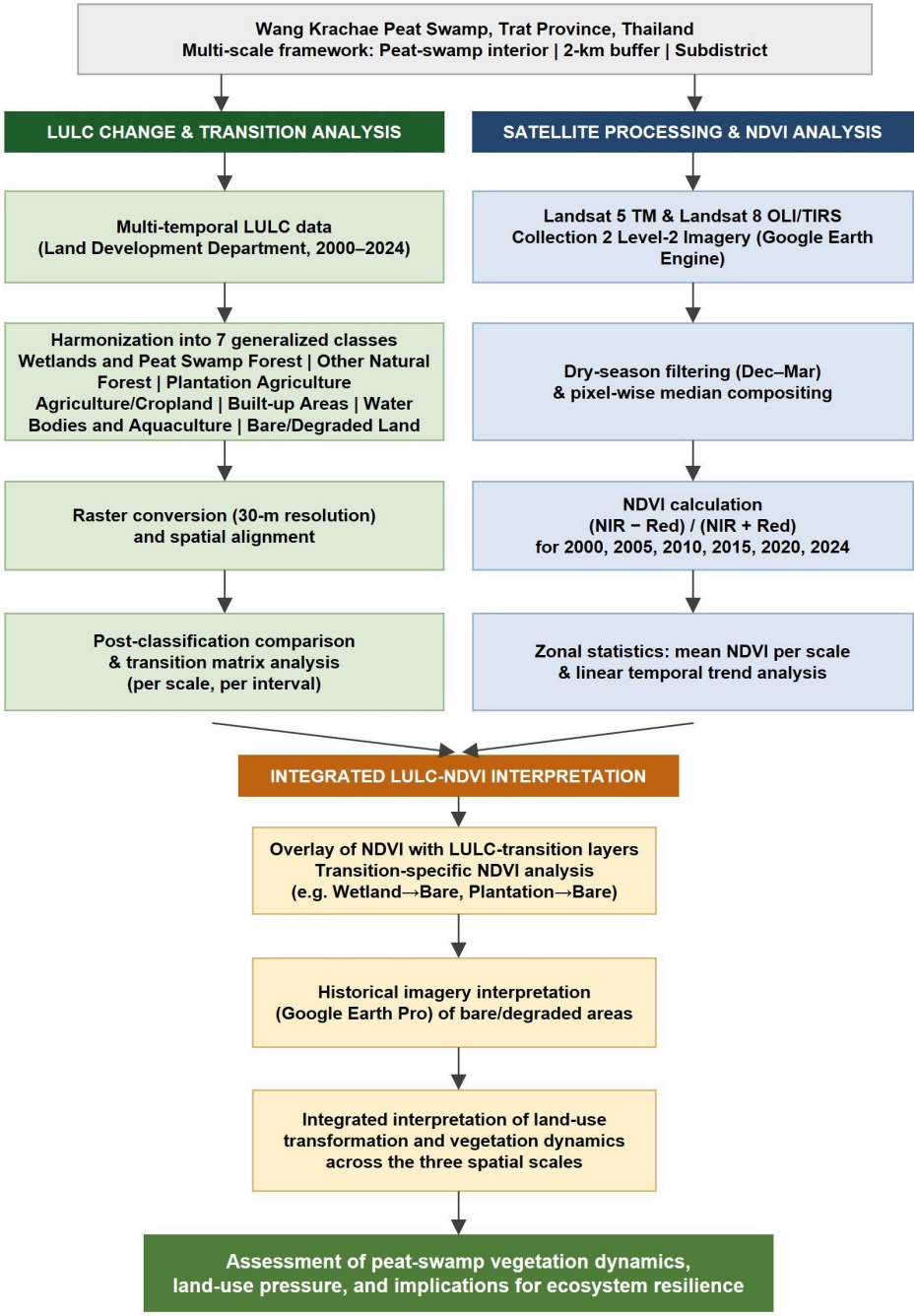


Figure 2. Methodological workflow for assessing land-use change and vegetation dynamics in the Wang Krachae Peat Swamp

3. RESULTS AND DISCUSSION

3.1 Multi-Scale Land-Use and Land-Cover Change

The LULC results

(Figure 3a-f) demonstrate that the peat-swamp interior remained predominantly Wetlands and Peat Swamp Forest, although its proportional coverage declined from 95.41% in 2000 to 88.81% in 2024. The decline was not uniform through time: wetland coverage fell sharply to 88.17% in 2005, recovered to 92.15% in 2010, and subsequently declined to approximately 88.81% by 2024. At the same time, Plantation Agriculture increased from 3.59% in 2000 to 10.80% in 2024. In this landscape, plantation agriculture is dominated by rubber cultivation, which accounted for 93.7% of plantation area

on average across the study period, with oil palm, coconut, and teak comprising the remainder. Agriculture/Cropland increased substantially during the period. This pattern indicates that the peat-swamp interior retained a large proportion of natural wetland cover but gradually saw increases in anthropogenic land uses (Figure 4a). Such transformation is consistent with broader evidence that tropical peatlands in Southeast Asia have been increasingly modified through agricultural and plantation conversion, drainage, and other human disturbances [4, 6, 19].

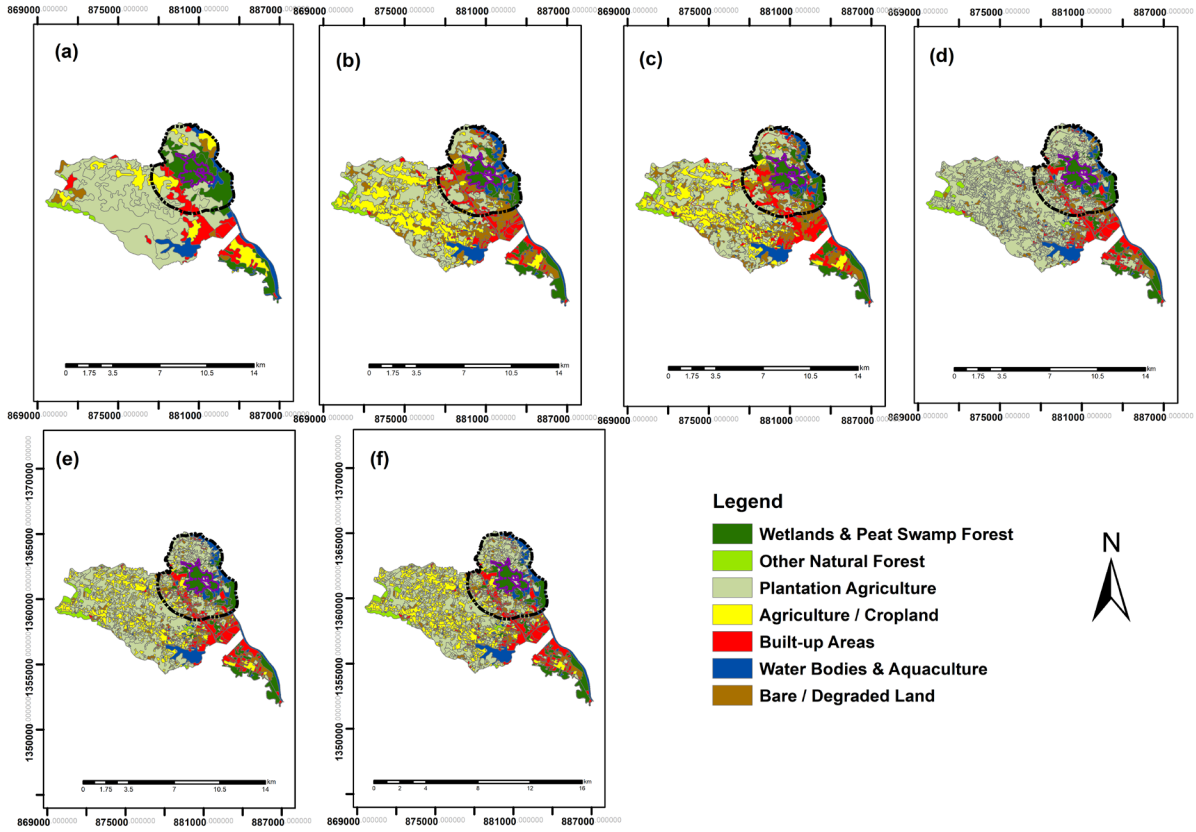


Figure 3. Spatial distribution of land-use and land-cover classes in the study area across the six assessment years: (a) 2000, (b) 2005, (c) 2010, (d) 2015, (e) 2020, and (f) 2024 (purple border represents peat-swamp and black border represents 2km buffer zone)

The surrounding 2-km buffer showed a stronger transformation than the peat-swamp interior (Figure 4b). Wetlands and Peat Swamp Forest declined from 39.57% (1,144.50 ha) in 2000 to 21.13% (611.15 ha) in 2024, representing a reduction of 533.35 ha. In contrast, Plantation Agriculture increased from 32.22% (932.04 ha) to 39.48% (1,141.93 ha), while Built-up Areas increased from 9.65% to 11.96%. Bare/Degraded Land also expanded sharply from 2.58% (74.49 ha) in 2000 to 22.34% (646.46 ha) in 2005, before declining to 6.82% (197.32 ha) by 2024. The buffer therefore experienced a much more pronounced restructuring of land cover than the peat-swamp interior, particularly through the conversion of wetland and plantation areas into bare/degraded land during the earlier period.

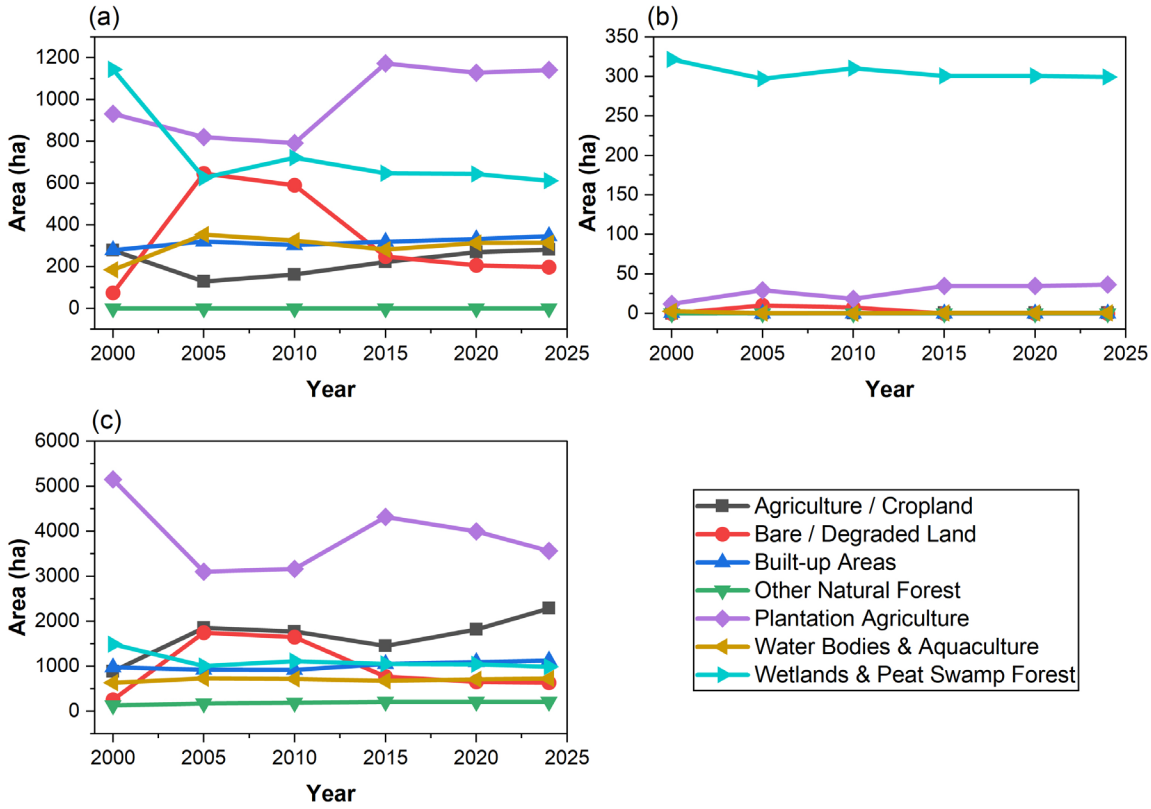


Figure 4. Temporal changes in LULC area across the three spatial scales: (a) peat-swamp interior, (b) 2 km buffer, and (c) surrounding sub-district, 2000–2024

This surrounding-landscape transformation matters because peatland degradation is often linked to interconnected processes of vegetation clearance, land conversion, drainage, and disturbance that operate beyond the immediate boundaries of remaining peat-swamp vegetation [6, 19, 20].

The sub-district-level landscape showed an even stronger trend toward Agriculture/Cropland and continued to include Plantation Agriculture. (Figure 4c). Agriculture/Cropland increased from 9.31% (886.68 ha) in 2000 to 23.98% (2,283.88 ha) in 2024, an increase of 1,397.20 ha. Plantation Agriculture was a key land-use category, fluctuating significantly, at 37.41% (3,563.10 ha) in 2024 compared with 54.12% (5,155.23 ha) in 2000. Meanwhile, Wetlands and Peat Swamp Forest declined from 15.64% (1,489.47 ha) to 10.36% (986.99 ha), a reduction of 502.48 ha. These results show that the peat swamp lies within a substantially modified agricultural and plantation landscape. Agricultural expansion, plantation development, and related land-use change are also important drivers of tropical peatland transformation in Southeast Asia, as identified in regional literature [4, 6, 21].

Overall, results across the three scales showed a clear spatial gradient: natural wetland cover was relatively stable in the interior of peat swamps, while transformation was more pronounced in the buffer and wider sub-district. This indicates that although some internal wetlands remain largely natural, they are being overlaid by a landscape dominated by agricultural and plantation uses. The results are thus consistent with the need to consider the peat swamp condition, not just from changes within the peat swamp boundary, but also the wider landscape context around the peat swamp, due to the effects of landscape fragmentation and conversion to intensively managed landscapes that may make existing natural peat swamp more vulnerable to external disturbing forces [19, 22].

3.2 Major LULC Transitions and Landscape Pressure

The transition patterns for the three spatial scales were broadly similar, in that there was a sharp period of land clearance and conversion from 2000 to 2005, and plantation expansion over both this newly cleared land and the natural wetland, while the peat-swamp interior was comparatively stable throughout (Table 2).

This period (2000-2005) represents the most dramatic change at the buffer and sub-district level. At the sub-district level, Plantation Agriculture lost 1,439.76 ha to Agriculture/Cropland and 812.77 ha to Bare/Degraded Land, while 174.53 ha and 332.36 ha were converted from Wetlands and Peat Swamp Forest to Bare/Degraded Land and Plantation Agriculture, respectively. The same trend is observed at a smaller scale in the buffer zone, with 258.90 ha of wetlands converted to Bare/Degraded Land and 168.34 ha to plantation. The most predominant signature in this period in both zones is the ability to map more than one source class being converted to Bare/Degraded Land, reflecting vegetation clearance as a first step in land preparation instead of a final state, and a conversion sequence that has been documented elsewhere in the region [21, 23].

Table 2. Major LULC transitions and corresponding areas (ha) across the three spatial scales during successive periods between 2000 and 2024

Spatial zone	Period	Transition		Area (ha)
		From	To	
Peatland interior	2000–2005	Wetlands & Peat Swamp Forest	Plantation Agriculture	28.79
		Wetlands & Peat Swamp Forest	Bare/Degraded Land	9.59
		Plantation Agriculture	Wetlands & Peat Swamp Forest	11.67
		Bare/Degraded Land	Wetlands & Peat Swamp Forest	2.60
	2005–2010	Wetlands & Peat Swamp Forest	Wetlands & Peat Swamp Forest	297.02
		Plantation Agriculture	Plantation Agriculture	18.38
		Bare/Degraded Land	Wetlands & Peat Swamp Forest	2.60
	2010–2015	Wetlands & Peat Swamp Forest	Wetlands & Peat Swamp Forest	293.43
		Wetlands & Peat Swamp Forest	Plantation Agriculture	16.62
		Bare/Degraded Land	Wetlands & Peat Swamp Forest	6.79
		Plantation Agriculture	Plantation Agriculture	17.96
	2015–2020	Wetlands & Peat Swamp Forest	Wetlands & Peat Swamp Forest	300.70
		Plantation Agriculture	Plantation Agriculture	34.88
	2020–2024	Wetlands & Peat Swamp Forest	Wetlands & Peat Swamp Forest	299.18
		Wetlands & Peat Swamp Forest	Plantation Agriculture	1.52
		Plantation Agriculture	Plantation Agriculture	34.88
		Agriculture/Cropland	Agriculture/Cropland	0.58
		Water Bodies & Aquaculture	Water Bodies & Aquaculture	0.72
2-km buffer	2000–2005	Wetlands & Peat Swamp Forest	Bare/Degraded Land	258.90
		Wetlands & Peat Swamp Forest	Plantation Agriculture	168.34
		Plantation Agriculture	Bare/Degraded Land	170.43
		Plantation Agriculture	Built-up Areas	89.29
		Agriculture/Cropland	Bare/Degraded Land	83.30
	2005–2010	Plantation Agriculture	Bare/Degraded Land	50.91
		Bare/Degraded Land	Wetlands & Peat Swamp Forest	84.27
		Plantation Agriculture	Wetlands & Peat Swamp Forest	12.36
		Bare/Degraded Land	Plantation Agriculture	27.43
		Agriculture/Cropland	Plantation Agriculture	7.50

Table 2. Major LULC transitions and corresponding areas (ha) across the three spatial scales during successive periods between 2000 and 2024 (cont.)

Spatial zone	Period	Transition		Area (ha)
		From	To	
2-km buffer	2010–2015	Bare/Degraded Land	Plantation Agriculture	208.45
		Wetlands & Peat Swamp Forest	Plantation Agriculture	109.06
		Agriculture/Cropland	Plantation Agriculture	74.46
		Bare/Degraded Land	Agriculture/Cropland	59.55
		Wetlands & Peat Swamp Forest	Built-up Areas	22.59
	2015–2020	Plantation Agriculture	Agriculture/Cropland	36.64
		Bare/Degraded Land	Water Bodies & Aquaculture	34.20
		Plantation Agriculture	Bare/Degraded Land	21.95
		Agriculture/Cropland	Bare/Degraded Land	2.34
		Wetlands & Peat Swamp Forest	Plantation Agriculture	3.66
	2020–2024	Wetlands & Peat Swamp Forest	Plantation Agriculture	20.95
		Plantation Agriculture	Agriculture/Cropland	16.46
		Wetlands & Peat Swamp Forest	Water Bodies & Aquaculture	5.12
		Agriculture/Cropland	Plantation Agriculture	4.70
		Plantation Agriculture	Built-up Areas	2.86
Sub-district	2000–2005	Plantation Agriculture	Agriculture/Cropland	1,439.76
		Plantation Agriculture	Bare/Degraded Land	812.77
		Wetlands & Peat Swamp Forest	Bare/Degraded Land	332.36
		Agriculture/Cropland	Bare/Degraded Land	263.11
		Built-up Areas	Bare/Degraded Land	229.36
		Wetlands & Peat Swamp Forest	Plantation Agriculture	174.53
		Wetlands & Peat Swamp Forest	Water Bodies & Aquaculture	158.83
	2005–2010	Bare/Degraded Land	Agriculture/Cropland	59.76
		Agriculture/Cropland	Plantation Agriculture	147.73
		Bare/Degraded Land	Wetlands & Peat Swamp Forest	100.40
		Plantation Agriculture	Bare/Degraded Land	102.76
		Wetlands & Peat Swamp Forest	Plantation Agriculture	8.86
	2010–2015	Agriculture/Cropland	Plantation Agriculture	660.21
		Bare/Degraded Land	Plantation Agriculture	552.42
		Bare/Degraded Land	Agriculture/Cropland	174.70
		Plantation Agriculture	Agriculture/Cropland	161.30
		Wetlands & Peat Swamp Forest	Plantation Agriculture	117.19
		Wetlands & Peat Swamp Forest	Built-up Areas	73.12
	2015–2020	Plantation Agriculture	Agriculture/Cropland	377.53
		Agriculture/Cropland	Plantation Agriculture	56.17
		Plantation Agriculture	Bare/Degraded Land	46.43
		Bare/Degraded Land	Plantation Agriculture	44.20
		Wetlands & Peat Swamp Forest	Built-up Areas	18.23
	2020–2024	Plantation Agriculture	Agriculture/Cropland	491.22
		Wetlands & Peat Swamp Forest	Plantation Agriculture	31.28
		Agriculture/Cropland	Plantation Agriculture	52.08
		Plantation Agriculture	Bare/Degraded Land	27.72
		Wetlands & Peat Swamp Forest	Water Bodies & Aquaculture	10.63
		Wetlands & Peat Swamp Forest	Built-up Areas	10.39

A substantial proportion of this transitional bare land was converted between 2010 and 2015, not to restored wetlands, but to plantations. During this period, 660.21 ha of Agriculture/Cropland were converted to Plantation Agriculture, an additional 552.42 ha of previously Bare/Degraded Land were converted to Plantation Agriculture in the sub-district, and 117.19 ha of direct wetland-to-plantation conversion occurred. That wetland loss (109.06 ha) occurred within the 2 km buffer and was therefore in close proximity to the peat swamp itself. Plantation growth in this landscape appeared to be partly driven by new clearance, but much of it involved converting natural wetland and existing cropland. This pattern has also been recorded for oil-palm expansion in other peatlands in Thailand, where natural wetlands and existing cropland were also converted [23]

The interior of the peat swamp presents a different situation. A stable core of 297.02-300.70 ha of Wetlands and Peat Swamp Forest remained in all periods between 2005 and 2024. Conversion of wetlands to plantations within the interior did not cease but remained relatively small (1.52 ha) from 2020 to 2024. This suggests that erosion along the interior margins is proceeding slowly, while the extent of landscape restructuring farther inland remains unclear. Over time, this ongoing loss may reduce both the extent and connectivity of the remaining natural habitat, even within a nominally protected core [21, 22, 24]. The transition patterns between these periods (2000-2005 land clearance and 2010-2015 plantation establishment) provide important context for interpreting the subsequent NDVI analysis.

3.3 NDVI Dynamics Across the Three Spatial Scales

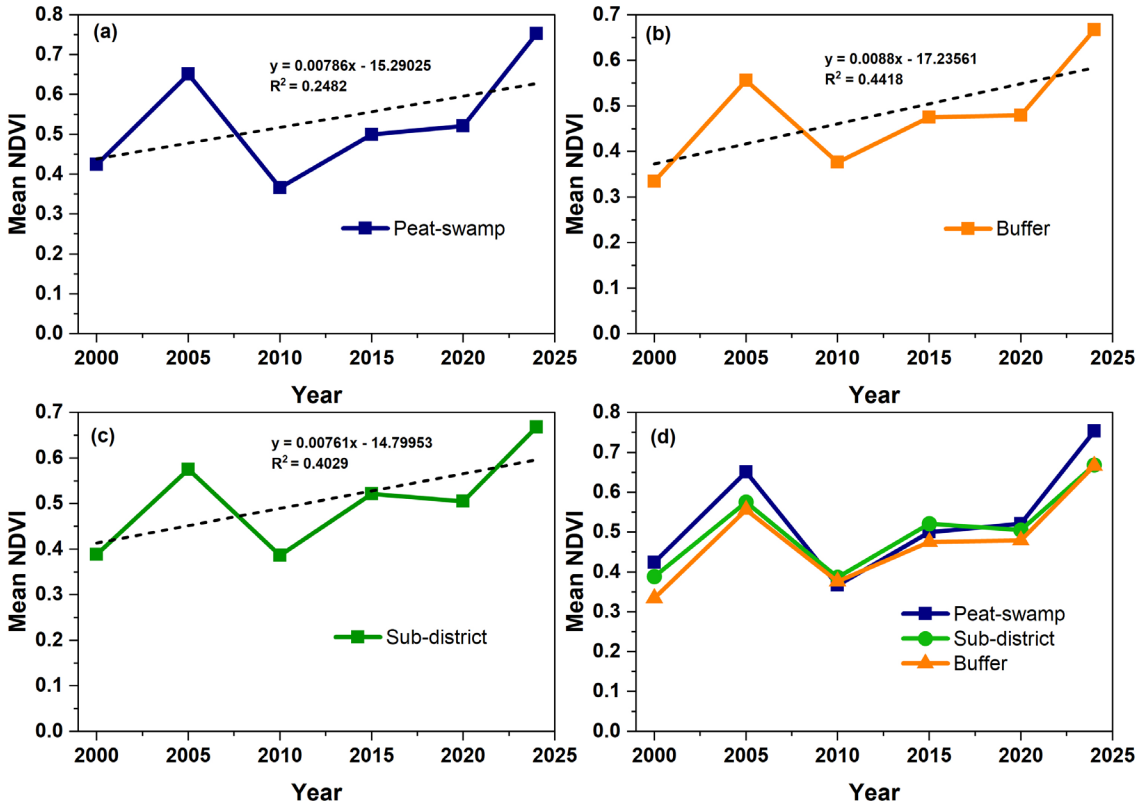


Figure 5. Temporal trends in mean NDVI from 2000 to 2024 for (a) the peat-swamp interior, (b) the 2-km buffer, (c) the surrounding subdistrict, and (d) comparative NDVI trends across the three spatial scales.

NDVI showed a similar temporal trajectory across all three spatial scales (Figure 5a-d, shown for each scale), with a marked decline between 2005 and 2010. In the peat-swamp interior, mean NDVI decreased from 0.6509 to 0.3664 (43.7%), while the buffer and sub-district declined by 32.3% and

32.8%, respectively. The stronger decline within the peat-swamp interior indicates that vegetation greenness was particularly affected during this period. NDVI is widely used to detect temporal changes in vegetation conditions and responses to environmental disturbance [13, 25].

The 2005-2010 NDVI decline coincided with the period of substantial LULC disturbance identified in the transition analysis, particularly the extensive transitions toward Bare/Degraded Land. Although this temporal agreement does not establish direct causation, the consistency between the LULC and NDVI trajectories indicates that the period represented a significant phase of vegetation disturbance across the study landscape. The stronger response within the peat-swamp interior further emphasizes its sensitivity to land-use transformation. Following 2010, NDVI increased across all scales, reaching 0.7529 in the peat-swamp, 0.6665 in the buffer, and 0.6681 in the sub-district by 2024. This demonstrates substantial recovery of vegetation greenness after the disturbance period. However, increased NDVI does not necessarily indicate recovery of the original natural wetland ecosystem, as regrowth or the establishment of managed vegetation can also increase greenness [20].

This temporal uniformity is remarkable because LULC change was more pronounced in the interior peat swamp, whereas overall LULC change was relatively minor during the study period. In contrast, NDVI changed substantially more in the interior than in the buffer and sub-district areas (43.7% compared with 32.3–32.8%). The decrease between 2005 and 2010 may not be attributed solely to the observed land-use change but could also reflect a region-wide climatic effect on vegetation greenness across all three scales, including areas under different land-use intensities. This interpretation is consistent with independent studies reporting widespread and significant vegetation stress in the region in 2005 and 2010, associated with regional drought conditions [24]. Thus, the steeper interior decline, despite the lower disturbance index from land use, is likely exacerbated by the sensitivity of intact peat swamp forest canopy to climatic stress, as well as by perhaps lower but localized land-use change (Table 2).

3.4 Implications for Peat-Swamp Conservation

The findings across the three spatial scales do not indicate a one-size-fits-all solution; instead, they suggest different levels of conservation priority. However, conversion within the peat-swamp interior has been relatively slow, with most conversion occurring along the margins, likely because the FIO protects and manages the area. Nevertheless, wetlands have continued to be converted to plantations in small, localized patches, particularly during 2020–2024 [21, 22, 24]. This pattern suggests that, rather than extensive interior monitoring, focused boundary monitoring may be a more effective conservation strategy for detecting and tracking encroachment along peat-swamp margins.

The 2 km buffer faces the highest immediate threat to the peat swamp. This is followed by early and severe transformation (2000-2005) and the direct conversion of 109.06 ha of buffer wetland to plantation (2010-2015), placing this loss directly adjacent to the peat swamp boundary. The buffer, rather than the interior, could be prioritized for protection or restriction in this zone, since land-use pressure has already measurably encroached on the interior in this instance [22, 24, 26].

However, at the sub-district scale, wetlands are proportionally lost, and the amount of change in the landscape from plantation-to-cropland churn (491.22 ha) over only a four-year period (2020-2024) shows that the landscape is in constant, large-scale change as farmers continue to restructure their crops. This broader instability is not a concern for conserving remaining wetland area, but it indicates compounding landscape pressures relevant to the hydrology and connectivity of the peat swamp's surroundings, and it is important to consider in conservation planning even if it does not lead to direct wetland conversion.

Finally, the NDVI recovery after 2010 should not be read as ecological recovery. NDVI reflects changes in environmental moisture and climatic variability as well as vegetation condition [13, 27], and can increase through plantation growth as readily as through wetland regeneration; natural peat-swamp structure, composition, and ecological function recover only over a much longer timeframe than

vegetation greenness alone [26, 28]. Monitoring based on NDVI alone therefore risks mistaking successful plantation establishment for genuine wetland recovery; tracking actual land-use class alongside NDVI, as done here, is necessary to avoid this false signal.

3.5 Limitations

This study explicitly acknowledges several limitations. First, this analysis is based exclusively on optical remote sensing (LULC classification and NDVI), which provides information on spatial persistence and vegetation greenness but does not directly provide information on the hydrological integrity of the peat swamp system, the condition of the subsoil peat, or biodiversity. Proxies of land-use conversion and vegetation greenness do not necessarily indicate ecological status, and structural or hydrological degradation can occur without a detectable land-cover or NDVI signal. Future work that includes hydrological monitoring (e.g., water table depth, drainage density) or field-based biodiversity assessment would greatly strengthen this interpretation.

Secondly, the interpretation of the historical Google Earth Pro images was qualitative and performed by one interpreter without independent cross-validation, and the formal classification accuracy assessment was also done by one interpreter. This classification may be subject to subjectivity bias, and the formal accuracy assessment was performed only for 2024 because high-resolution historical reference imagery became more available that year, with no formal assessment of classification accuracy for 2000-2020. Multi-interpreter cross-validation and independent accuracy assessments across multiple assessment years, where possible, would be useful rather than relying solely on a single reference year.

Third, the outer spatial scale of this study is based on administrative divisions, which do not perfectly match the peat swamp's hydrological catchment, and the upper, non-administratively bounded part of the surrounding landscape was not analyzed. This decision aligned with the administrative datasets used for this analysis and their association with landscape-scale hydrology influencing the peat swamp, but it may not reflect the true breadth of landscape-scale hydrologic influence on the peat swamp. Patterns identified here could be extended beyond the administrative sub-district using a hydrologically defined catchment boundary or using concentric buffers.

4. CONCLUSIONS

This study demonstrates that land-use change alone is insufficient to assess peatland condition. Although the peatland interior remained relatively unchanged in land-cover classification from 2000 to 2024, it experienced the greatest vegetation stress across the three spatial scales during the 2005–2010 disturbance period and continues to undergo gradual loss along its margins while remaining relatively stable overall. Multi-scale analysis shows that the greatest land-cover transformation occurred not within the protected core but in the surrounding buffer zone, and that NDVI recovery does not necessarily indicate ecological recovery. These findings support a nature-based approach to peatland management at Wang Krachae that prioritizes the protection of intact wetlands from degradation and targets interventions according to the dominant pressures at each spatial scale, rather than treating the peat swamp as a single, homogeneous unit. This approach may also be relevant to other small, human-pressured tropical peatlands in Thailand experiencing similar surrounding land-use changes. Future research should integrate optical remote sensing with hydrological and subsurface indicators, incorporate independent multi-interpreter validation, and evaluate hydrologically defined catchment boundaries against the administrative boundary used here to determine whether the observed patterns extend beyond the current study area.

Acknowledgement

The authors thank the Forest Industry Organization, Thailand, for providing spatial data and site access in support of this study. The first author acknowledges support from the Chulalongkorn University Graduate Scholarship Program for ASEAN or Non-ASEAN Countries, Chulalongkorn University, Bangkok, Thailand.

References

[1] Kurnianto, S., et al., Carbon accumulation of tropical peatlands over millennia: a modeling approach. Global Change Biology, 2015. 21(1): p. 431–44.
[2] Ribeiro, K., et al., Tropical peatlands and their contribution to the global carbon cycle and climate change. Global Change Biology, 2021. 27(3): p. 489–505.
[3] Page, S., et al., Anthropogenic impacts on lowland tropical peatland biogeochemistry. Nature Reviews Earth & Environment, 2022. 3(7): p. 426–443.
[4] Cole, L.E.S., K.J. Willis, and S.A. Bhagwat, The future of Southeast Asia's tropical peatlands: Local and global perspectives. Anthropocene, 2021. 34.
[5] Page, S.E. and A.J. Baird, Peatlands and Global Change: Response and Resilience. Annual Review of Environment and Resources, 2016. 41(1): p. 35–57.
[6] Dohong, A., A.A. Aziz, and P. Dargusch, A review of the drivers of tropical peatland degradation in South-East Asia. Land Use Policy, 2017. 69: p. 349–360.
[7] Wösten, J.H.M., et al., Peat–water interrelationships in a tropical peatland ecosystem in Southeast Asia. Catena, 2008. 73(2): p. 212–224.
[8] Intergovernmental Panel on Climate Change (IPCC), Climate change 2022: Mitigation of climate change. Cambridge University Press, 2022.
[9] Pielke, R.A., Pitman, A., Niyogi, D., Mahmood, R., McAlpine, C., Hossain, F., et al., Land use/land cover changes and climate: Modeling analysis and observational evidence. Wiley Interdisciplinary Reviews: Climate Change, 2011. 2(6): p. 828–850.
[10] Leifeld, J. and L. Menichetti, The underappreciated potential of peatlands in global climate change mitigation strategies. Nature Communications, 2018. 9(1): p. 1071.
[11] Bonn, A., et al., Peatland restoration and ecosystem services: nature-based solutions for societal goals, in Peatland Restoration and Ecosystem Services. 2016. p. 402–417.
[12] Zhu, Z., S. Qiu, and S. Ye, Remote sensing of land change: A multifaceted perspective. Remote Sensing of Environment, 2022. 282.
[13] Pettorelli, N., et al., Using the satellite-derived NDVI to assess ecological responses to environmental change. Trends in Ecology & Evolution, 2005. 20(9): p. 503–10.
[14] Hansen, A.J. and R. DeFries, Ecological mechanisms linking protected areas to surrounding lands. Ecological Applications, 2007. 17(4): p. 974–88.
[15] Wangritthikraikul, K., Ladd, S. N., Santos, R. N., Haghipour, N., Dubois, N., & Chawchai, S. (2026). Multi-proxy reconstruction of Holocene paleoenvironmental changes in eastern Thailand: Sea-level and monsoon as key drivers. Quaternary Science Reviews, 392, 110248.
[16] Wilson, J. D., Anderson, R., Bailey, S., Chetcuti, J., Cowie, N. R., Hancock, M. H., Quine, C. P., Russell, N., Stephen, L., & Thompson, D. B. A. (2014). Modelling edge effects of mature forest plantations on peatland waders informs landscape-scale conservation. Journal of Applied Ecology, 51(1), 204–213.
[17] Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., & Moore, R. (2017). Google Earth Engine: Planetary-scale geospatial analysis for everyone. Remote Sensing of Environment, 202, 18–27.
[18] Pontius, R.G. Jr., et al., Detecting important categorical land changes while accounting for persistence. Agriculture, Ecosystems & Environment, 2004. 101(2–3): p. 251–268.
[19] Girkin, N.T., et al., Tropical peatlands in the Anthropocene: The present and the future. Anthropocene, 2022. 40.
[20] Hergoualc'h, K. and L.V. Verchot, Stocks and fluxes of carbon associated with land use change in Southeast Asian tropical peatlands: A review. Global Biogeochemical Cycles, 2011. 25(2).
[21] Miettinen, J., C. Shi, and S.C. Liew, Land cover distribution in the peatlands of Peninsular Malaysia, Sumatra and Borneo in 2015 with changes since 1990. Global Ecology and Conservation, 2016. 6: p. 67–78.
[22] Posa, M.R.C., L.S. Wijedasa, and R.T. Corlett, Biodiversity and conservation of tropical peat swamp forests. BioScience, 2011. 61(1): p. 49–57.
[23] Srisunthon, P. and S. Chawchai, Land-Use Changes and the Effects of Oil Palm Expansion on a Peatland in Southern Thailand. Frontiers in Earth Science, 2020. 8.
[24] Mishra, S., et al., Degradation of Southeast Asian tropical peatlands and integrated strategies for their better management and restoration. Journal of Applied Ecology, 2021. 58(7): p. 1370–1387.
[25] Ha, T. V., Uereyen, S., & Kuenzer, C. (2024). Spatiotemporal analysis of tropical vegetation ecosystems and their responses to multifaceted droughts in Mainland Southeast Asia using satellite-based time series. GIScience & Remote Sensing, 61(1), 2387385.

[26] Graham, L.L.B., W. Giesen, and S.E. Page, A common-sense approach to tropical peat swamp forest restoration in Southeast Asia. Restoration Ecology, 2016. 25(2): p. 312–321.
[27] Huang, S., et al., A commentary review on the use of normalized difference vegetation index (NDVI) in the era of popular remote sensing. Journal of Forestry Research, 2020. 32(1): p. 1–6.
[28] Tomita, M. and Y. Hirabuki, et al., Vegetation recovery on a degraded peatland following a severe fire: Results of a 6-yr period study in Southeastern Thailand. TROPICS, 2007. 16(2).