SPATIAL ANALYSIS OF FOREST FRAGMENTATION IMPACTS ON ECOSYSTEM SERVICES IN PETALING, MALAYSIA (2005–2023)

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ABSTRACT

Forest fragmentation poses a critical threat to ecosystem service functionality, particularly in rapidly urbanizing regions. This study investigates the spatio-temporal dynamics of forest fragmentation and its impacts on two essential ecosystem services, water provisioning and recreational value, within the Petaling District, Selangor, Malaysia, across the years 2005, 2014, and 2023. Using Landsat satellite imagery, supervised classification, and key landscape metrics (patch size, edge density, and connectivity), the research identified clear signs of intensified fragmentation. Although there was partial forest recovery post-2014, increased patchiness and elevated edge densities indicated persistent structural degradation. To understand how fragmentation affects ecosystem services at a local scale, the study used Geographically Weighted Regression (GWR). GWR is a spatial econometric approach that captures local variations and spatial non-stationarity. This is in contrast to conventional global models which assume uniform relationships across space. Significant spatial heterogeneity was found in the influence of fragmentation metrics on water provisioning and recreational services. The results can be interpreted as site-specific and thus important for adaptive conservation planning. Fragmentation metrics were found to influence water provisioning and recreational services unevenly across the landscape, with proximity to water bodies and developed areas serving as proxy indicators. Notably, areas with high edge density and reduced patch sizes were more vulnerable to hydrological service loss, while recreational value exhibited a spatially complex relationship, influenced by accessibility and landscape aesthetics. The findings underscore the urgent need for spatially adaptive planning and proactive forest governance, especially in urbanizing districts. By integrating ecological indicators with spatial econometrics, this research offers nuanced, site-specific insights that support conservation prioritization and sustainable land use strategies. The methodological framework and results contribute to broader discussions on urban ecological resilience and ecosystem service preservation under accelerating land-use pressures in tropical regions.

Keywords: spatial ecology, landscape change, urban ecology, forest resilience, ecosystem mapping

INTRODUCTION

Natural resources form the cornerstone of human survival, serving as essential components of the environment that fulfill a wide array of societal functions. In the face of rapid urbanization, industrial growth, and spatial expansion driven by burgeoning population pressures, these resources are under unprecedented stress. Human interventions have extensively transformed the natural landscape, frequently resulting in adverse ecological consequences. This poses serious threats to key elements of human well-being as outlined in the Millennium Ecosystem Assessment (MA, 2005), namely security, access to basic materials for a decent life, social cohesion, and the autonomy to make choices. Among the vital ecological systems, intact and dense forests are particularly significant for their multifunctional role in providing timber, regulating ecological cycles such as nutrient flow and water filtration, and supporting recreational and ecotourism activities. Lamy *et al.* (2016) emphasize that the spatial configuration of landscapes, including patch shape and connectivity; plays a crucial role in the delivery of ecosystem services. This insight foregrounds the significant impact of forest fragmentation, especially within rapidly urbanizing areas, on the continuity and effectiveness of these services.

The concept of ecosystem services offers a valuable analytical framework to understand how natural processes contribute to human benefit. Originating in the late 1970s with a utilitarian view of ecological functions (Westman, 1977), the term has since evolved to encompass a broad spectrum of direct and indirect benefits derived from nature. Ecosystem services effectively link biophysical processes to societal well-being by translating ecological functions into tangible and, at times, monetarily valued outputs. This valuation is facilitated by methodologies such as the Ecosystem Services Valuation (ESV), developed through collaborations by the Ecosystem Services Partnership (ESP) and the Foundation for Sustainable Development (FSD). The present study is grounded in the framework provided by the Millennium Ecosystem Assessment (MA), a comprehensive UN-sponsored initiative carried out between 2001 and 2005 (Layke, 2009). The MA provided compelling evidence that over the past fifty years, human activity has inflicted significant and often irreversible damage to global ecosystems, resulting in substantial biodiversity loss and deterioration of ecosystem services. These services, when linked to human welfare, demonstrate a critical cause-and-effect relationship, where the degradation of ecosystems directly undermines the constituents of human well-being. The MA categorizes ecosystem services into four key domains: provisioning services (e.g., food, water, timber), regulating services (e.g., climate and water regulation), supporting services (e.g., nutrient cycling and soil formation), and cultural services (e.g., spiritual and recreational benefits) (Liu *et al.*, 2023). Simultaneously, it outlines the principal elements of human well-being susceptible to ecological degradation, which include security, social relationships, material needs, and individual freedom. Alarmingly, despite their indispensable role, these services are rapidly declining due to intensified environmental degradation.

This study particularly addresses the phenomenon of forest fragmentation, an increasingly critical issue given its proven influence on the supply, distribution, and resilience of ecosystem services (Mitchell *et al.*, 2014; Zhang & Gao, 2016; Lamy *et al.*, 2016; Metzger *et al.*, 2021; Assis *et al.*, 2023; Biswas *et al.*, 2023). Forest fragmentation is conceptualized as a landscape-scale process where continuous forest tracts are broken into smaller, isolated patches due to anthropogenic interventions such as illegal logging, infrastructure development, and urban sprawl (Hazwan *et al.*, 2022). These fragmented landscapes lead to loss of ecological connectivity, reduction in habitat diversity, and diminished landscape quality for human and wildlife interactions (Jaeger *et al.*, 2006; Mitchell *et al.,* 2014). Fragmentation significantly disrupts the natural movement of organisms, genetic material, and ecological processes (Suwannaphong *et al.*, 2024). For example, the interruption of riparian ecosystems impairs their ability to regulate water flow, quality, and retention, ultimately compromising the availability of freshwater for both flora and fauna. This leads to cascading effects such as a decline in plant populations, wildlife migration, and heightened incidents of human-wildlife conflict. Moreover, increased fragmentation introduces edge effects, reduces core habitat size, and raises the frequency of human access routes, each of which heightens ecosystem vulnerability (Fahrig, 2003). The intricate interplay between fragmentation and ecosystem functionality underlines the urgency for empirical investigation and robust modeling to quantify these impacts. Currently, there exists a significant research gap in the precise measurement of how forest fragmentation affects ecosystem service delivery, highlighting the need for further studies to build an evidence-based understanding of this complex relationship.

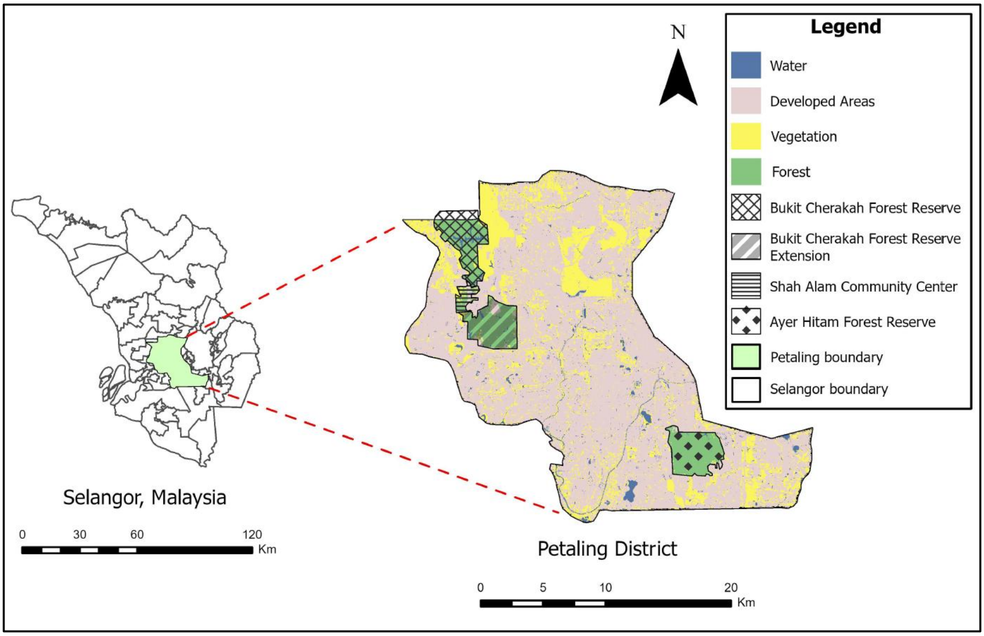
There is an increasing empirical study which clearly associates forest fragmentation with the decline of ecosystem services. Most of the existing studies depend on global statistical models which assume relationships to be constant across space (Zhang & Gao, 2016; Lamy *et al*., 2016). These methods cannot adequately articulate the spatial heterogeneity of ecological processes in a rapidly urbanizing tropical context, such as Petaling, where local land-use dynamics and environmental responses per locality significantly vary. Therefore, this restricts total contextual understanding by policymakers or planners for them to institute site-specific conservation interventions. To address that methodological gap, therefore, Geographically Weighted Regression (GWR) shall be applied in this study because it is a spatial econometric technique capable of capturing non-stationary relationships between forest fragmentation metrics and ecosystem services delivery. GWR, and not a global model, shows how the strength and direction of these relationships vary by location, thereby offering a much more nuanced and context-sensitive understanding of forest-ecosystem service interactions (Fotheringham *et al*., 2002; Zhao *et al*., 2018; Ran *et al*., 2023). Hence, it provides new spatially explicit evidence to support adaptive forest management and urban ecological planning. Forest fragmentation is also significantly recreational valued in such an urbanizing landscape as Petaling fragments accessibility to green spaces, landscape aesthetics, and opportunities for eco-tourism, hiking, and environmental education-related recreation activities. These impacts are amplified in areas where green spaces are under pressure from development because the quality of recreational experiences reduces public involvement with nature. The decline in spatial continuity of forests thus not only affects biodiversity and ecosystem functioning but also infringes on the social and cultural benefits that urban dwellers derive from these spaces.

MATERIALS AND METHODOLOGY

Study area

This study centers on two significant forest reserves in the state of Selangor, Malaysia: Bukit Cherakah Forest Reserve and Ayer Hitam Forest Reserve; both situated within the rapidly urbanizing Petaling District (Fig. 1). Geographically positioned at 3.1846° N and 101.5360° E, Petaling spans approximately 486.99 square kilometers and had an estimated population of 2.19 million in 2021. The district comprises four principal administrative divisions or *mukim*: Sungai Buloh, Damansara, Petaling, and Bukit Raja. Over the past two decades, Petaling District has experienced significant urban expansion, with its population growing from approximately 1.5 million in 2000 to over 2.19 million in 2021 (City Population Portal, 2023; Department of Statistic Malaysia, 2023). This rapid population growth has been a major driver of land-use changes, contributing to the fragmentation of natural habitats and increasing pressure on the remaining green spaces. While Ayer Hitam Forest Reserve is known for eco-educational purposes, Bukit Cherakah Forest Reserve provides recreational opportunities as well, with hiking trails and other activities involving the community. However, due to the unavailability of actual usage data, the study resorted to using proximity to residential areas as indicative of its recreational value. Much less safe to assume that this kind of proximity fully reflects complexities in the demand for recreation which would include aspects of security to visitors among others.

Fig. 1: Map of land covers and forest reserve boundaries situated in Petaling district, Selangor, Malaysia



The primary focus of the investigation is the Bukit Cherakah Forest Reserve, located in Shah Alam. This ecological zone, once encompassing 12,892 hectares, has been significantly reduced to 2,281.66 hectares by 2022 due to sustained urban encroachment (Fig. 1). The forest reserve is now surrounded by expanding residential and commercial developments, notably Setia Alam, Denai Alam, and Elmina. Despite this reduction, Bukit Cherakah remains ecologically significant due to its dense dipterocarp vegetation, typical of Peninsular Malaysia’s lowland tropical rainforests (Hasmadi & Al, 2017). The Tropical Rainforest Conservation & Research Center (TRCRC), in its 2021 biodiversity assessment, identified the presence of several endangered species recognized by the IUCN Red List, including the Malayan Tapir, Southern Pig-tailed Macaque, White-handed Gibbon, and Dusky Langur (IUCN, 2021). Currently, the reserve exists as three fragmented zones: the Bukit Cherakah Permanent Forest Reserve, its Extension (which includes Bukit Cahaya and Taman Botani Negara Shah Alam), and the Shah Alam Community Forest. The latter plays a crucial role as an ecological corridor linking the other two forest patches. However, this connectivity is increasingly threatened by intensifying urbanization, which has led to habitat degradation, pollution, and rising human-wildlife conflicts (Ma *et al.*, 2024). Without strategic interventions, the ecological integrity of Bukit Cherakah is at risk of further deterioration under relentless development pressure (Laurance *et al.*, 2021).

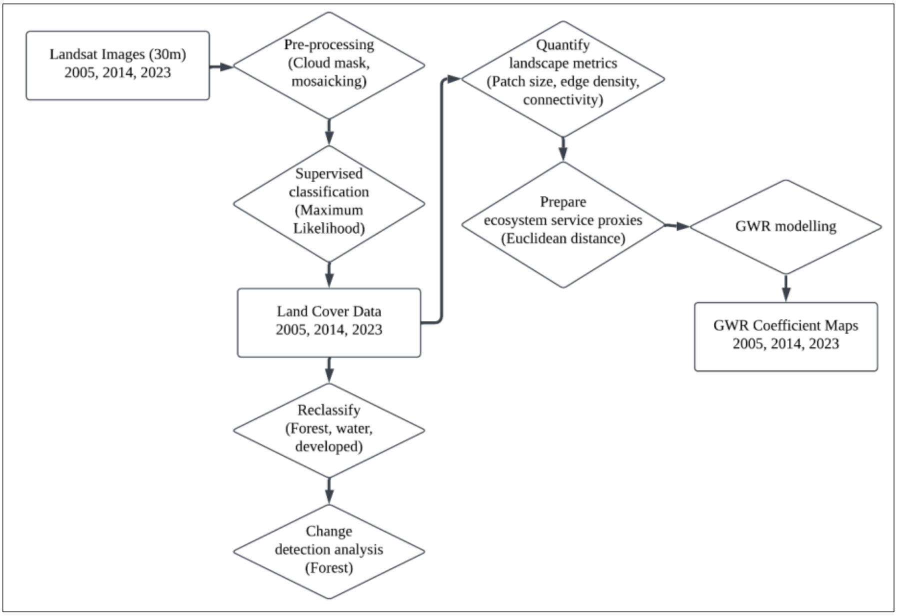
The second site under investigation is the Ayer Hitam Forest Reserve, located in Puchong. This reserve, once covering 4,270 hectares in 1906, has diminished to approximately

1,176 hectares due to rapid industrialization and urban expansion (Hasmadi & Al, 2017; Siti *et al*., 2022). Designated as a permanent forest reserve, it is currently managed under a long-term lease by Universiti Putra Malaysia (UPM). The establishment of the Sultan Idris Shah Forestry Education Centre within the reserve has enabled sustained ecological research and educational activities, enhancing the reserve's scientific and conservation value. Ayer Hitam is home to an impressive array of biodiversity, comprising over 430 species of flowering plants, 127 tree species, 208 bird species (35 of which are classified as endangered), and five of the ten large mammal species found in Peninsular Malaysia. It is strategically positioned near key urban centers, including Petaling Jaya, Kuala Lumpur, Shah Alam, and Cyberjaya, functioning as a critical ecological buffer and green lung. The reserve plays an essential role in carbon sequestration, air purification, and water regulation via Sungai Rasau (Siti *et al*., 2022). Its historical logging roads, dating back to the 1930s-1980s, have been repurposed as access pathways, facilitating research and eco-education. With its diverse dipterocarp assemblages and established research infrastructure, Ayer Hitam offers a unique living laboratory for advancing knowledge in urban ecology, conservation science, and forest restoration, underscoring both its ecological vulnerability and its promise as a model site for sustainable forest management in a highly urbanized landscape.

The analytical workflow for spatio-temporal assessment of forest fragmentation and ecosystem services

Fig. 2 presents a comprehensive methodological framework adopted in this study to analyze the spatio-temporal dynamics of forest fragmentation and its influence on ecosystem services, specifically water provisioning and recreational value, across three temporal intervals: 2005, 2014, and 2023. This integrative workflow combines remote sensing, geospatial analysis, landscape metrics, and spatial econometric modeling to systematically evaluate landscape transformations and their ecological implications.

Fig. 2: The methodological flowchart



The collection of dataset

This study adopts a spatio-temporal analytical framework to investigate the dynamic relationship between forest fragmentation and key ecosystem services, specifically focusing on water provisioning and recreational functions. To capture land cover changes over time, remote sensing data were derived from Landsat satellite imagery for the years 2005, 2014, and 2023, utilizing a spatial resolution of 30 meters from both Landsat 7 ETM+ and Landsat 8 OLI/TIRS sensors (Table 1). This level of resolution is deemed appropriate for detecting substantial landscape transformations, with prior studies affirming classification accuracies exceeding 85 % for similar land use assessments (Hussain *et al.*, 2024).

Table 1: The details of dataset used in study

Data	**Details**	**Source**
Satellite imagery (2005, 2014 and 2023)	Raster, 30m, Landsat 7 and 8	US Geological Survey (USGS)
Administrative boundaries	Shapefile, polygon	Humanitarian Data Exchange (https://data.humdata.org/dataset/)
Study area boundary		Manually digitized, georeferencing Google Earth
Land cover data		Classification of land cover done using ArcGIS Pro

Landscape metrics

Landscape metrics provide a robust quantitative framework for assessing the extent and pattern of forest fragmentation, employing key indicators such as patch size, edge density, spatial connectivity, core area, and the nearest-neighbour index (Fahrig, 2003; Abdullah, 2016) (Table 2). As deforestation and reforestation processes continue to evolve across global landscapes, a range of models and analytical tools have emerged to evaluate fragmentation dynamics, contributing to more informed strategies for forest conservation, protection, and ecological restoration. Among these, landscape metrics serve as essential instruments for objectively quantifying changes in forest structure over time. Patch size refers to the total area of contiguous vegetation, offering insights into habitat availability. Edge density quantifies the cumulative length of fragment boundaries, often associated with reductions in interior or core habitat. Spatial connectivity assesses the degree to which patches are linked or isolated within the broader landscape matrix, while the nearest-neighbour index evaluates the proximity between individual patches, capturing patterns of isolation or connectedness that influence ecological flows and species movement.

Table 2: Overview of landscape metrics used to determine forest fragmentation.

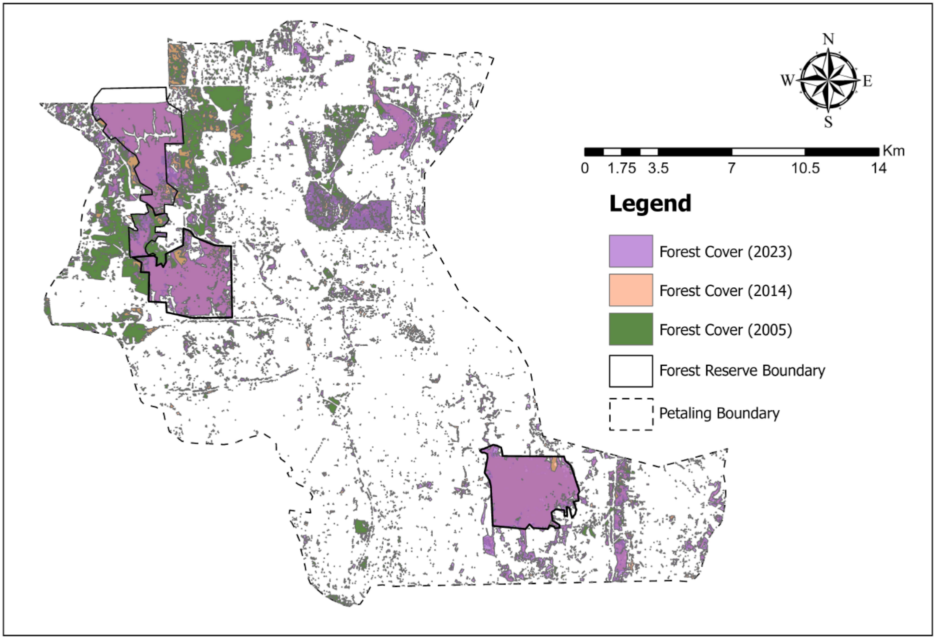
Landscape metrics	Description/ Details	Literature Source
Patch size	Area of individual and isolated forest fragments or land cover units Smaller patch sizes generally indicate higher levels of fragmentation	(McGarigal & Marks, 1995)
Edge density	The sum of the lengths (m) of all edge segments in the landscape, divided by the total landscape area (m2)	(McGarigal et al., 2002)
	Total linear edge in a landscape can be divided by the area of the landscape to provide a single edge-to-area estimate	(Cardille & Turner, 2017)
	Large edge density maintains habitat structures and indicates a higher level of biodiversity	(Hussain et al., 2024)
Connectivity	Structural connectivity - connectivity is based entirely on landscape structure Functional connectivity - considers organisms' behavioral responses to individual landscape elements (patches and edges) and the spatial configuration of the entire landscape	(Kindlmann & Burell, 2008)

Geographically Weighted Regression (GWR)

The Geographically Weighted Regression (GWR) model is employed in this study to analyze spatially varying relationships between forest fragmentation and ecosystem services at both localized and landscape scales (Jamaludin, 2017). Unlike conventional regression techniques that assume spatial uniformity, GWR excels in capturing spatial heterogeneity, offering nuanced insights into how relationships differ across geographical locations. This is particularly significant for ecological studies, as environmental processes and their impacts are rarely homogenous across space. As noted by Fotheringham *et al*. (2002), the spatial variation in regression coefficients generated by GWR enables a clear visualization of heterogeneous interactions, making it an ideal analytical tool for this study. The model is applied to evaluate the influence of forest fragmentation on two ecosystem services, water provisioning and recreational value, across three temporal benchmarks: 2005, 2014, and 2023. GWR's ability to detect non-stationary patterns allows for the identification of spatial clusters where fragmentation impacts are either intensified or attenuated (Ran *et al*., 2023). This approach facilitates a more detailed and location-specific interpretation of fragmentation effects, revealing localized vulnerabilities and zones of ecological concern. In the context of the Bukit Cherakah Forest Reserve, GWR illuminates the spatial distribution of impacts on ecosystem services, thus offering critical insights into the differentiated nature of environmental degradation across the study area. Unlike global regression models that assume spatial homogeneity over the entire area, such as Ordinary Least Squares (OLS), GWR permits its coefficients to vary locally. In this manner, it captures variations in the relationship between metrics of forest fragmentation and any service at different locations, reflecting real-world relationships that are themselves heterogeneous across space. This is particularly true and useful in rapidly urbanizing tropical regions wherein environmental processes plus human pressures vary considerably from site to site within a relatively small area; thus making detail, context-specific analyses similar to those provided by GWR both appropriate as well as necessary. Besides GWR, a hybrid GWR-InVEST model was used that incorporates the spatial econometrics of GWR with the ecosystem service mapping abilities of the InVEST model. While GWR obtains local variation in the relationship between fragmentation metrics and ecosystem services, the InVEST model maps and quantifies the flow of ecosystem services such as water provisioning and recreational value. More explicit spatial detail added through this approach enhances an understanding of tradeoffs between land use and delivery of ecosystem services (Liang *et al.,* 2024).

Land cover data critical to this study were derived through supervised classification employing the Maximum Likelihood algorithm, a method known for its statistical accuracy in multispectral image interpretation. Utilizing the classification framework from the National Land Cover Dataset (2011), five primary land cover categories, forest, water, developed, barren, and planted/cultivated, were selected as training samples. For the purpose of focused analysis, only forest, water, and developed classes were extracted and further processed. The ‘forest’ class specifically represents areas with tree canopy cover within the Petaling District, and forest extent was quantified using pixel-based area calculations. To assess temporal changes in forest structure, land cover data for the years 2005, 2014, and 2023 were spatially overlaid, allowing for visual and quantitative change detection, as illustrated in Fig. 3. This multi-temporal comparison enables the identification of both forest loss and fragmentation trends across nearly two decades.

Fig. 3: Change detection over temporal scope



Ecosystem Services Assessment

This paper selects two categories of ecosystem services by the Millennium Ecosystem Assessment (MA): (1) water provisioning to represent a provisioning service and (2) recreational value to represent a cultural service. The selection is theoretically significant and methodological rather than selective. Conceptually, they provide the most feasible links between ecological structure and human well-being in an urbanizing tropical landscape. Hydrological processes comprising water provisioning include infiltration, flood mitigation, and groundwater recharge, continuity of spatial forest cover hydrologically relies on land use policies either supporting or disrupting such continuity (Assis *et al.*, 2023; Metzger *et al.*, 2021). In practical policy-oriented biophysical research accounting exercises such processes are immediately affected by policies that either support or disrupt such continuity therefore this paper selects them as preferred indicators.

From a methodological point of view, these two categories were selected because they can be quantified through spatially explicit proxy indicators that allow geospatial and econometric modeling. Water provisioning is represented by proximity to water bodies while recreational value is represented by proximity to residential areas thus ensuring analytical consistency within the Geographically Weighted Regression (GWR) framework. On the other hand, regulating and supporting services such as carbon sequestration or nutrient cycling require process-based biophysical models with much higher resolution data requirements than what this study's timeframe or spatial extent could accommodate. The focus on provisioning and cultural services ensures analytical consistency, reproducibility as well as policy relevance meanwhile future research could extend this framework into other ecosystem service categories when more data becomes available (Layke, 2009; Metzger *et al.*, 2021; Assis *et al.*, 2023; Ran *et al.*, 2023).

Quantifying Ecosystem Services using proxy indicators

Due to difficulties in direct measurement of ecosystem services, proxy indicators are used in the present study to show the effect of forest fragmentation on water provisioning and recreational value. These are practical and easily observable indicators reflecting eventually the service function itself. For assessing water provisioning, distance to the nearest water bodies has been used as a proxy indicator. This, in fact, is an approach widely accepted among spatial ecological studies representing hydrological ecosystem services since proximity to streams or wetlands or rivers is positively associated with groundwater recharge as well as infiltration and water regulation capacity (De Groot *et al.*, 2010; Biswas *et al.*, 2023). Ran *et al.* (2023) and Zhao *et al.* (2018) also prove through GWR and other similar spatial modeling approaches that areas nearer to water bodies always carry higher provisioning service flows due to better hydrological connectivity.

For recreational value, the proximity of residential locations to forests or green areas is used as a proxy indicator. This has been validated in several other frameworks for ecosystem service valuation, where accessibility becomes a key determinant of recreational utility (Stessens *et al.*, 2017). Accessibility-based proxies are quite pertinent in regions where cities are encroaching upon because it reflects both aspects-the spatial availability of green infrastructure and sociocultural demand for nature-based recreation (Paracchini *et al.*, 2014; Liang *et al.*, 2024). More importantly though is that if the forest lies close to residential communities there would be high potential opportunities for recreational activities involving social bonding. The proxy-based assessments, therefore, align with the established practices of spatial ecosystem service modeling and allow for consistent geospatial analysis within the GWR framework. They permit translation of landscape metrics into quantifiable indicators of ecosystem service functionality thus enabling ecologically sound, yet policy-relevant spatially explicit insight.

RESULTS AND DISCUSSION

Forest structural dynamics in the Petaling District

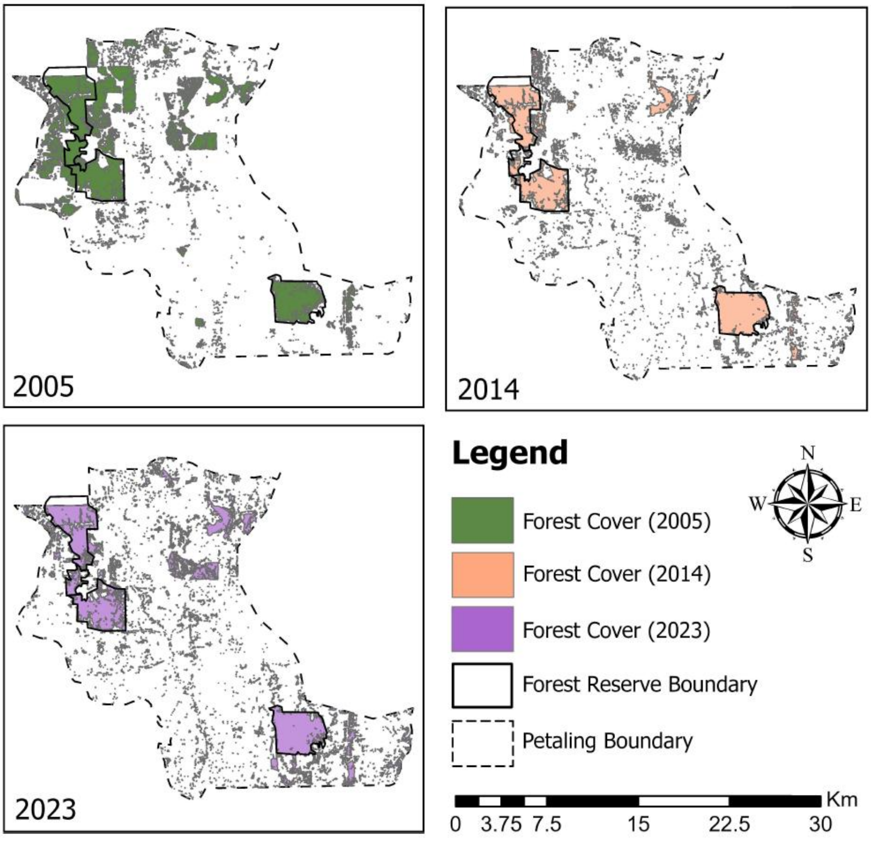
Table 3 provides detailed data on total forested area and the corresponding number of discrete forest patches identified for each time frame, highlighting the spatial patterns and intensification of fragmentation within the study area.

Table 3: Temporal changes of forest area in Petaling district

Year	Forest Area (ha)	Number of Patches
2005	7723	2149
2014	5278	3440
2023	6455	3774

As illustrated in Fig. 4, the total forest area within the Petaling District was estimated at 7,723 hectares in 2005, represented in green. This figure declined substantially by 2014 to 5,278 hectares (depicted in orange), before experiencing a moderate increase to 6,455 hectares in 2023. While this partial recovery suggests reforestation efforts or land cover transition, further analysis reveals more complex underlying structural transformations. Key landscape metrics, namely patch size, edge density, and connectivity, provide critical insights into the spatial configuration of forested areas. Larger mean patch sizes typically symbolize more cohesive and uninterrupted forest cover supporting higher biodiversity along with the ecosystem service delivery (Fahrig, 2003; McGarigal *et al.*, 2002). Such large patches shall most probably have better interior habitat quality with lower edge effects that make ecological stability and resilience beneficial to Abdullah & Nakagoshi (2007); Mitchell *et al.* (2014). Whereas an increasing number of smaller, isolated patches indicates progressive fragmentation. Edge density, which measures the ratio of forest edge length to total area, generally rises when larger patches are subdivided, amplifying edge effects that influence habitat integrity. Connectivity evaluates the spatial proximity and potential ecological linkage among forest patches and is shaped by both the extent of forest cover and its spatial distribution. A quantitative examination of patch counts underscores this trend toward fragmentation. In 2005, 2,149 discrete forest patches were identified. This number surged to 3,440 in 2014 and further increased to 3,774 in 2023. The steady rise in patch numbers across the three temporal snapshots signals intensifying forest fragmentation, despite the observed partial gain in total forest area post-2014. This suggests that forest regeneration has occurred in a fragmented or spatially disconnected manner, with newly vegetated areas forming smaller, non-contiguous patches rather than consolidating existing ones. Such spatial restructuring reduces ecological connectivity; fragmentation isolates habitat patches; Harrison & Bruna (1999) and McGarigal & Marks (1995) describe this as making it difficult for species to migrate or interact across the landscape. As connectivity increases, ecological processes begin to be facilitated by gene flow and species dispersal including hydrological regulation of ecosystems (Forman, 2014). Unlike studies from other tropical urban landscapes, such as those in Southeast Asia (Abdullah & Nakagoshi, 2007), this study records a higher degree of patch fragmentation in Petaling, even allowing for reforestation efforts after 2014. High edge densities and small patch sizes are indicative of substantial hindrances to connectivity functions long before partial recoveries of forest areas engender connectivity optimism among ecologists. Comparable results were obtained by Biswas *et al*. (2023) in Indian urban forests where increases in the edge effects due to fragmentation reduced biodiversity as well as ecosystem service levels purportedly available within the same landscape. What makes this case different or special is that here again rapid urbanization appears more likely than not to be accelerating gradual processes elsewhere reported primarily from other tropical regions.

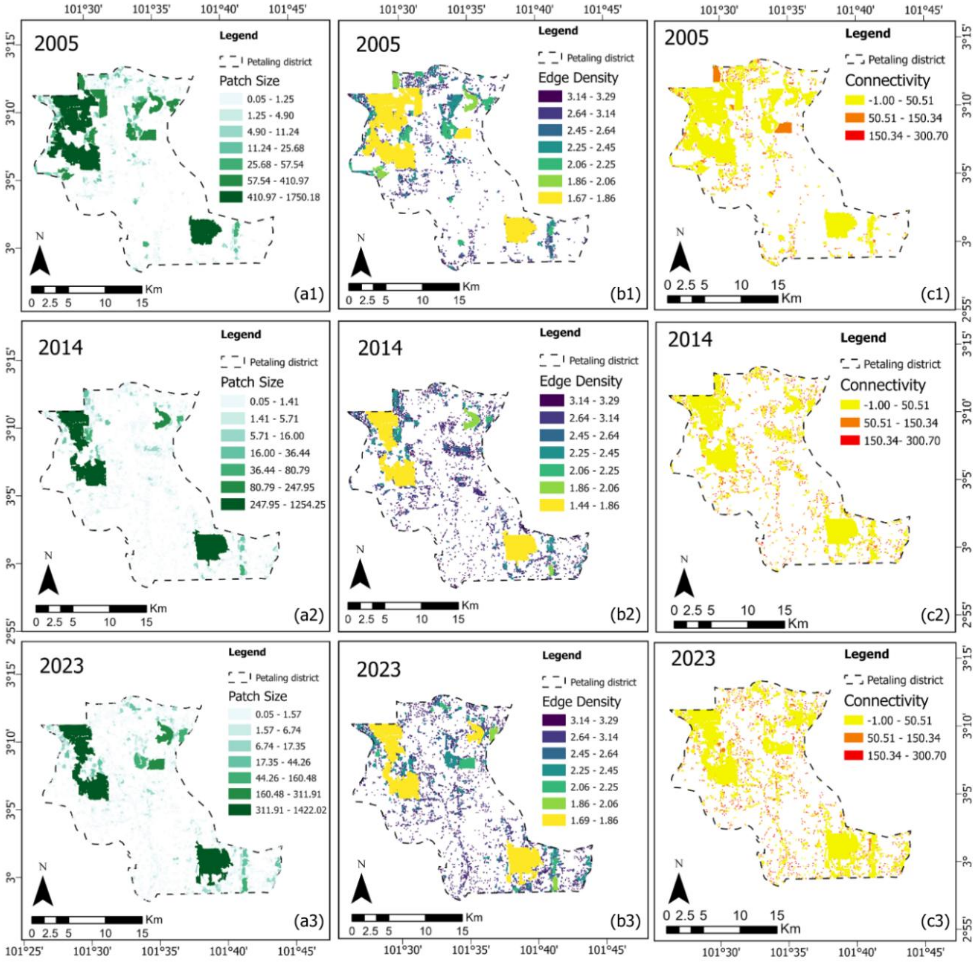
Fig. 4: Forest cover maps for each year



Landscape Metrics and Fragmentation Dynamics

To evaluate the influence of forest fragmentation on ecosystem service delivery, this study employed a targeted selection of landscape metrics, namely average patch size, edge density, and connectivity. Although the literature identifies a broad array of landscape metrics, relying on individual indices in isolation often yields limited interpretative value. Therefore, a composite approach was adopted to capture complementary aspects of spatial structure and fragmentation. These metrics collectively provide a more comprehensive understanding of forest configuration and its evolution across the study period. The computed average values are summarized in Table 4 and visually represented in Fig. 5.

Fig. 5: Landscape metrics:
(a1) Patch size measured for 2005, (a2) patch size measured for 2014, (a3) patch size measured for 2023, (b1) edge density measured for 2005, (b2) edge density measured for 2014, (b3) edge density measured for 2023, (c1) connectivity measured for 2005, (c2) connectivity measured for 2014, (c3) connectivity measured for 2023.



In 2005, the forest landscape was characterized by a relatively high degree of spatial cohesion, with an average patch size of approximately 3.59 hectares. This indicates the presence of large, contiguous forested areas. Concurrently, the average edge density was measured at 1,356.90 meters per hectare, while mean inter-patch connectivity stood at 45.67 meters, suggesting that patches were moderately close to one another, supporting ecological continuity.

Table 4: Temporal changes of forest fragmentation in Petaling district

Year	Avg. Patch Size (ha)	Avg. Edge Density (m/ha)	Avg. Connectivity (m)
2005	3.593946	1356.903	45.66868
2014	1.534437	1425.756	56.83713
2023	1.710522	1414.864	55.01039

By 2014, notable structural changes had occurred. The average patch size sharply declined to 1.53 hectares, reflecting significant fragmentation and a breakdown of larger forest units into smaller, more isolated fragments. Edge density increased to 1,425.76 meters per hectare, a pattern consistent with the proliferation of patch boundaries and loss of core habitat. Connectivity also rose to 56.84 meters, indicating that the spatial gaps between forest patches had widened, further impeding ecological linkages. In 2023, a modest improvement in forest structure was observed. The average patch size slightly increased to 1.71 hectares, potentially suggesting localized reforestation or land cover stabilization. However, edge density remained elevated at 1,414.86 meters per hectare, only marginally lower than the 2014 figure, implying that fragmentation effects persisted. Mean connectivity decreased slightly to 55.01 meters, though still higher than in 2005, indicating that spatial isolation remained a challenge. These results reveal a dynamic yet fragmented forest landscape in transition. The consistent trend of increasing edge density coupled with reduced patch size underscores ongoing habitat fragmentation. Meanwhile, fluctuations in connectivity highlight the changing spatial arrangement of patches, whether they become more clustered or increasingly dispersed. These patterns are critical in understanding how forest structure evolves over time and how such transformations influence the capacity of landscapes to support key ecosystem services.

Geographically Weighted Regression (GWR) Results: Proximity to Water Bodies

The Geographically Weighted Regression (GWR) analysis revealed notable spatial heterogeneity in the relationship between forest fragmentation metrics and proximity to water bodies across the study area, underscoring the non-stationary nature of these interactions over time. As shown in Fig. 6, the spatial distribution of coefficient values varied considerably across the three temporal benchmarks: 2005, 2014, and 2023; reflecting the evolving landscape structure and its influence on hydrological ecosystem services (Table 5). Table 5 displays the coefficients together with standard deviations in the relationship of forest fragmentation metrics with proximity to water bodies. Positive coefficients for patch size imply that larger patches are nearer to water bodies, thus indicating an association between large tracts of forests and good hydrological service delivery. However, it ranges widely from -0.004 up to 0.276 which again signifies spatial heterogeneity wherein certain parts strongly manifest this positive relationship while others weakly or even negatively correlates with it. High standard deviation (0.033) also indicates how variable across landscape this relationship is. This therefore means that there has been effective regeneration of forests enhancing hydrological services in some areas while other fragmented patches still experience disruption on flow as well as quality regulation.

Table 5: GWR Coefficient Values Relative to Proximity to Water Bodies

Year	Metric	Min Coef	Max Coef	Mean Coef	Std Dev
2005	Patch size	-0.004	0.276	0.015	0.033
	Edge density	-0.016	-0.005	-0.012	0.002
	Connectivity	-0.136	0.071	0.001	0.057
2014	Patch size	-20.214	9.464	0.145	3.832
	Edge density	-0.029	0.030	-0.0006	0.008
	Connectivity	-0.456	0.787	0.058	0.204
2023	Patch size	-0.00006	0.0002	0.000007	0.00002
	Edge density	-0.018	0.022	0.004	0.010
	Connectivity	-0.336	0.282	-0.056	0.107

Nevertheless, there are limitations to the proximity-based proxies used in this study. While distance to water bodies can loosely represent hydrological services, it does not speak for the entire complexity of water provisioning that includes watershed dynamics, groundwater recharge, and regulation on water quality. The recreational value inferred from the proximity of settlements may not fully reflect actual recreational use due to accessibility and cultural or social preference factors. These limitations have to be borne in mind when reading the results and future research should attempt a more comprehensive ecosystem service modeling approach that better quantifies these services (such as InVEST). Although this study does not conduct classical tests of the significance of changes over time, GWR allows for an examination of the possibility that there is a spatially varying relationship between fragmentation metrics and ecosystem services. Thus, no test of statistical significance of change over time is necessary. GWR encapsulates local variation and spatial non-stationarity for the three temporal windows (2005, 2014, and 2023) to leverage greater detail on spatial heterogeneity and localized ecological dynamics developing over time. Therefore, this type of analysis brings out much richer spatial detail in interpretation concerning forest fragmentation impacts than can be provided by a conventional global model or time-based significance test.

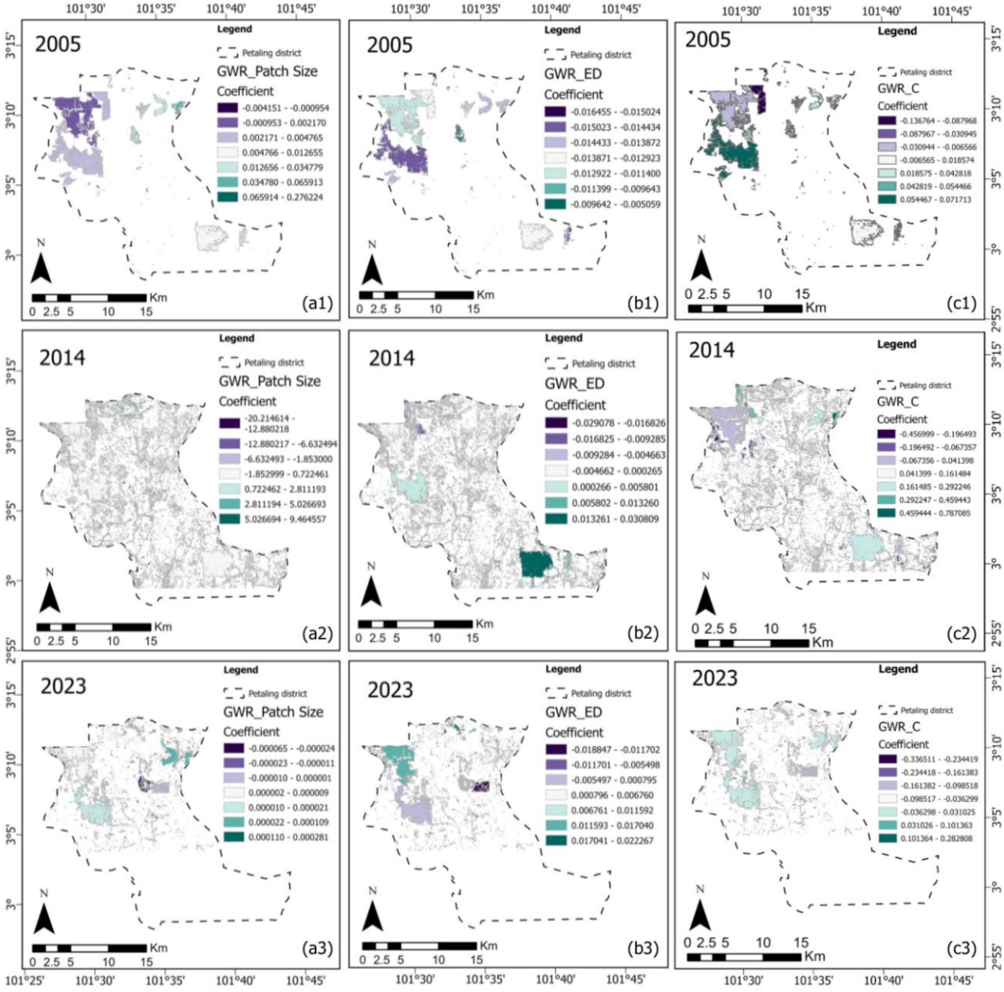
In 2005, the GWR output indicated a positive association between patch size and proximity to water bodies, with a mean coefficient of +0.015 and a range between –0.004 and +0.276 (standard deviation = 0.033). This suggests that larger forest patches were generally closer to water sources. Conversely, edge density exhibited a consistently negative relationship, with coefficients ranging from –0.016 to –0.005 and a mean of –0.012, implying that areas with more fragmented edges were generally farther from water bodies. Connectivity coefficients displayed a broader range (–0.136 to +0.071), with a mean near neutrality (+0.001) and a standard deviation of 0.057, indicating localized variations in spatial association.

By 2014, the spatial patterns had shifted significantly. The coefficient range for patch size expanded dramatically (–20.214 to +9.646), accompanied by an increased mean value of +0.145, suggesting intensified variability and stronger localized associations. Edge density showed a wider spread of values (–0.029 to +0.030), though the mean remained close to zero (–0.0006), indicating a weakening or neutralization of its spatial relationship with water bodies. Meanwhile, connectivity demonstrated a pronounced shift, with coefficients ranging from –0.456 to +0.787 and a higher mean value of +0.058, pointing to a stronger positive correlation in some areas and growing spatial divergence across the landscape.

In 2023, the coefficients reflected a general stabilization, particularly for patch size, which exhibited minimal variability (–0.00006 to +0.0002) and a near-zero mean (+0.000007), suggesting a diminishing influence of patch size on proximity to water bodies. Edge density maintained a relatively balanced spread (–0.018 to +0.022) with a slightly positive mean of +0.004, while connectivity coefficients ranged from –0.336 to +0.282, with a mean of –0.056, highlighting increasing spatial disconnection between forested areas and water resources.

These findings demonstrate the spatially dynamic nature of forest fragmentation impacts on hydrologically relevant ecosystem services. Over time, forest structural attributes such as patch integrity, edge complexity, and spatial arrangement have fluctuated in their influence on access and proximity to water bodies, reinforcing the importance of spatially explicit modeling approaches like GWR in capturing these complex ecological interactions.

Fig. 6: GWR coefficient maps relative to water proximity:
(a1) Patch size measured for 2005, (a2) patch size measured for 2014, (a3) patch size measured for 2023, (b1) edge density measured for 2005, (b2) edge density measured for 2014, (b3) edge density measured for 2023, (c1) connectivity measured for 2005, (c2) connectivity measured for 2014, (c3) connectivity measured for 2023.



Geographically Weighted Regression (GWR) Results: Proximity to Residential Areas

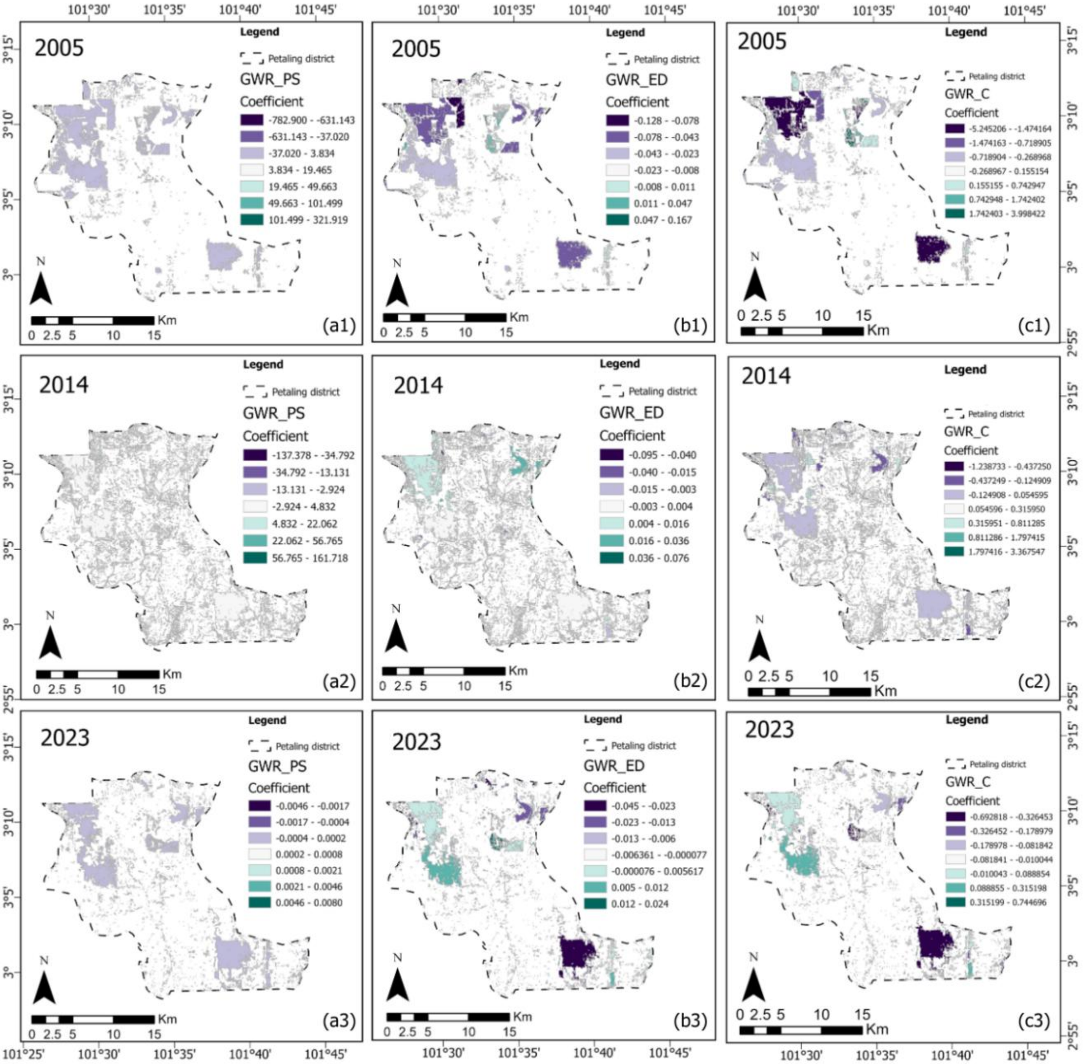
The GWR analysis examining proximity to developed areas, used as a proxy for recreational value, reveals significant spatial variability in the relationship between forest fragmentation metrics and accessibility to urban communities. Table 6 summarizes the minimum, maximum, mean coefficient values, and standard deviations for each landscape metric across the temporal scope of 2005, 2014, and 2023. These findings offer a spatially nuanced understanding of how forest structure influences potential recreational access over time, as further visualized in Fig. 7. Some of the coefficient ranges observed, such as those for patch size in 2005 (–782.900 to +321.919), may seem extreme. These values, however, represent the spatial heterogeneity of the relationship between fragmentation metrics and ecosystem services across Petaling District. This means there is substantial local variation in both the pattern of fragmentation and landscape structure within Petaling. Such extreme coefficients are not modeling errors but reflect real complex ecological dynamics at different micro-landscapes particularly where rapid urbanization and varying intensities of land use exist (Cabral *et al.*, 2012). The results support the necessity for a spatially explicit approach like GWR since localized patterns may be "averaged out" or masked by a global model.

Table 6: GWR Coefficient Values Relative to Proximity to Developed Areas

Year	Metric	Min Coef	Max Coef	Mean Coef	Std Dev
2005	Patch size	-782.900	321.919	7.955	33.444
	Edge density	-0.128	0.167	-0.013	0.028
	Connectivity	-5.245	3.998	-0.150	0.598
2014	Patch size	-137.378	161.718	0.455	12.068
	Edge density	-0.095	0.076	0.0003	0.014
	Connectivity	-1.238	3.367	0.007	0.302
2023	Patch size	-0.004	0.008	0.0002	0.001
	Edge density	-0.045	0.0246	-0.004	0.011
	Connectivity	-0.692	0.744	-0.040	0.124

Table 6 displays coefficients of fragmentation metrics with proximity to residential areas taken here as a proxy for recreational value. Positive connectivity coefficients (mean = 0.007 to 0.58) indicate that connectivity is more likely linked with better recreational opportunities close to green spaces or forests. The wide range of connectivity values (-5.245 to +3.998) again reflects high spatial variability in some parts which could be strong er recreational value areas due to very close proximity connections between green spaces and residential areas while other parts have weaker associations. The wide standard deviation (0.598) indicates that the spatial distribution of recreational value is very inconsistent in the Petaling district probably owing largely to differences in urban accessibility, availability as well as appeal (aesthetic) aspects of green spaces. The results reveal spatial heterogeneity both in hydrological and recreational services. Areas of high edge density and small patch sizes appear to be weaker in service delivery while more connected larger forest patches contribute better to both service deliveries. This variability in the effects of fragmentation on different parts of the landscape emphasizes the hydrological and recreational services provided by targeting areas with high levels of fragmentation but low connectivity where ecosystem services are more at risk.

Fig. 7: GWR coefficient maps relative to developed areas proximity:
(a1) Patch size measured for 2005, (a2) patch size measured for 2014, (a3) patch size measured for 2023, (b1) edge density measured for 2005, (b2) edge density measured for 2014, (b3) edge density measured for 2023, (c1) connectivity measured for 2005, (c2) connectivity measured for 2014, (c3) connectivity measured for 2023.



Several factors drive the observed spatial heterogeneity in the relationship between fragmentation and ecosystem services. Highly fragmented landscapes are created by urbanization within the Petaling District area, with spots of intensive development displaying much higher degrees of fragmentation than the surrounding forest patches. It is a result of historical agricultural and logging land uses that have also contributed to this pattern of fragmentation. Effects on ecosystem services from topographic features such as elevation and proximity to water bodies wherein higher elevation areas more often display better connectivity with larger patches existing appear to be an integrated complexity that needs understanding for effective conservation strategy planning within this region. In 2005, the relationship between patch size and proximity to residential areas exhibited substantial variation, with coefficients ranging from –782.900 to +321.919 (mean = +7.955, SD = 33.444), indicating highly localized and extreme effects across the study area. Edge density coefficients ranged between –0.128 and +0.167 (mean = –0.013), suggesting generally weak and inconsistent associations, while connectivity displayed a similarly wide spread from –5.245 to +3.998 (mean = –0.150, SD = 0.598), implying considerable heterogeneity in how forest spatial arrangements affected urban accessibility.

By 2014, a general reduction in coefficient variability was observed. Patch size coefficients narrowed to a range of –137.378 to +161.718, with a mean of +0.455, suggesting a more stabilized but still spatially diverse relationship. Edge density ranged from –0.095 to +0.076 (mean = +0.0003), and connectivity coefficients ranged from –1.238 to +3.367 (mean = +0.007), reflecting a continued shift towards more balanced yet differentiated spatial interactions. In 2023, the model indicated a marked convergence in coefficient values across all three metrics, suggesting increasing spatial uniformity. Patch size values ranged narrowly from –0.004 to +0.008 (mean = +0.0002), edge density from –0.045 to +0.0246 (mean = –0.004), and connectivity from –0.692 to +0.744 (mean = –0.040). These compressed ranges and lower mean values indicate a decline in the spatial sensitivity of forest structure on recreational accessibility, potentially due to either homogenization of the landscape or diminished forest-urban interface. Overall, the GWR results demonstrate a temporal trajectory of decreasing spatial variability in the influence of forest fragmentation on recreational ecosystem services. While earlier years showed pronounced local disparities in how patch characteristics correlated with residential proximity, recent patterns suggest a shift toward more spatially consistent but potentially weakened relationships. These findings emphasize the importance of incorporating spatial econometric techniques to uncover the localized and evolving impacts of forest fragmentation on socio-ecological functions.

Over the study's temporal span of 2005, 2014, and 2023, clear structural transformations were observed within the forest landscapes of the Petaling District. As visualized in Fig. 3, average patch sizes exhibited a consistent decline, while both edge density and connectivity showed increasing trends. These patterns are indicative of intensifying forest fragmentation, where previously contiguous ecosystems such as Bukit Cherakah and Ayer Hitam Forest Reserves have progressively disintegrated into smaller, more isolated patches. This trend parallels findings by Biswas *et al.* (2023) in Eastern India and earlier work by Abdullah & Nakagoshi (2007) in Selangor, highlighting the encroachment of urban development into forested areas. As urbanization accelerates, natural ecosystems become more disrupted, eroding their structural integrity and ecological functionality.

In Malaysia's tropical climate, the ecological consequences of increasing edge density are significant. Forest edges are more vulnerable to microclimatic changes, invasive species, and biophysical degradation. Over time, these edge effects undermine the forest's capacity to deliver consistent ecosystem services. This aligns with the findings of Kamlun *et al.* (2012), who, through Landsat-based analysis in Sarawak, demonstrated the reliability of moderate-resolution remote sensing in detecting forest structural degradation. Similar patterns are captured in this study's edge density trends (Fig. 5), where fragmentation, though not extreme in each time slice, has shown persistent progression, raising serious concerns about the long-term resilience of forest ecosystems and their capacity to support ecosystem service delivery.

The integration of Geographically Weighted Regression (GWR) modeling further enriches this spatial narrative by revealing localized relationships between forest fragmentation and ecosystem services. In the case of water provisioning, approximated by proximity to water bodies, the GWR model detected significant spatial non-stationarity. This condition, where relationships between variables differ across space, underscores the need to move beyond traditional regression models. The study reveals that the impact of landscape metrics (e.g., patch size, edge density, connectivity) on water provisioning varied considerably across the study area. Locations characterized by high edge density and smaller patches correlated with reduced water provisioning potential, likely due to disrupted hydrological processes such as infiltration, evapotranspiration, and flow regulation. These spatially explicit relationships are visualized in Fig. 6, highlighting zones of ecological vulnerability. These findings are consistent with Biswas *et al.* (2023), who noted that regions undergoing land-use and land-cover (LULC) transitions experienced corresponding declines in hydrological services, suggesting a shared underlying mechanism of ecological degradation.

This spatially explicit modeling approach makes a departure in the current study from earlier works that used global or non-spatial regression models (Zhang & Gao, 2016; Lamy *et al.*, 2016). By applying GWR, this paper highlights that the effects of forest fragmentation on ecosystem services are not homogeneous across Petaling but rather vary within the landscape. The capacity of GWR to detect local variations in coefficient strength and direction reveals patterns which would have been masked by conventional models-thereby empirically justifying more targeted conservation zoning and adaptive forest governance. This methodological advantage is echoed by Zhao *et al.* (2018), who employed GWR to examine complex urban-environment linkages, affirming the tool's sensitivity to localized variation. Fig. 6 and Fig. 7 in this study reveal spatially distinct deviations in ecosystem service relationships, enabling place-based conservation recommendations. Particularly in fragmented environments, where ecosystem processes do not respond uniformly to anthropogenic stressors, GWR is essential in identifying critical intervention areas. Unlike traditional global models, GWR uncovers spatial asymmetries that inform more nuanced ecological planning and prioritization strategies. In contrast, the modeling of recreational value, using proximity to developed areas as a proxy, produced more complex and less consistent patterns (Fig. 7). While proximity to developed areas occasionally aligned with increased recreational potential, this was not a uniform trend. Some forest patches retained moderate recreational value due to their accessibility, aesthetic appeal, or community usage, whereas others, especially those experiencing higher fragmentation, exhibited diminished associations. This variability reflects the inherently subjective nature of recreational value. Fragmentation may, in some contexts, enhance access and usage, while in others, it degrades the perceived naturalness and ecological integrity of the site. Liang *et al.* (2024), through a hybrid GWR-InVEST model, observed that patches exposed to intensive human activity often suffered reduced habitat quality and ecosystem value, findings mirrored in this study. While not all fragmentation leads to immediate functional loss, chronic disruption erodes both ecological and socio-cultural ecosystem benefits.

The potential long-term implications are profound. As emphasized by Biswas *et al.* (2023) and Laurance *et al.* (2021), unchecked urban expansion invariably leads to landscape degradation, threatening native biodiversity, habitat quality, and ecological aesthetics. In a densely urbanizing area like Petaling, this risk is particularly acute. Forests increasingly bordered by residential development face dual consequences: enhanced public access, which may promote nature appreciation and mental well-being, and increased ecological stress due to human disturbance. These include heightened foot traffic, pollution, wildlife disturbances, and the spread of invasive species, all of which contribute to a gradual, often imperceptible, ecological decline. The loss of recreational ecosystem services, in this sense, extends beyond ecology into the realm of socio-psychological well-being. As fragmentation increases, forests may lose their symbolic and cultural meanings, reducing their role as places of escape, reflection, and connection with nature. Despite the valuable insights yielded by this study, several limitations must be acknowledged. A primary constraint was the availability of consistent, high-resolution satellite imagery. Due to image quality and cloud cover, especially for the year 2014, only three temporal benchmarks (2005, 2014, and 2023) were selected. This temporal limitation restricted a more granular analysis of landscape transitions. Additionally, the use of proxy indicators, such as proximity to water bodies and developed areas, provides only indirect estimates of ecosystem service dynamics. While useful, these proxies do not fully encapsulate the complex biophysical and perceptual dimensions of water provisioning and recreational value. For instance, distance to water does not necessarily reflect watershed function or groundwater recharge capacity, just as proximity to development does not inherently predict actual recreational use or perceived value.

Furthermore, while GWR is powerful in revealing spatial heterogeneity, its effectiveness is constrained without field validation. The absence of ground-truth data in this study may affect the reliability of the spatial relationships detected. While the accuracy of the classifications was assumed based on previous studies and literature citations, this does not take into account any local variations that could occur in Petaling District. As satellite-derived classifications are always prone to error-influencing factors such as cloud cover, seasonality, and heterogeneity in the landscape, site-specific validation would have provided more accurate results. As such, future research should incorporate field-based ecological measurements and stakeholder feedback to enhance model accuracy and empirical relevance. Ground-truthing would strengthen the robustness of spatial modeling and expand the scientific validity of the conclusions drawn. In essence, this study advances the discourse on forest fragmentation by combining landscape metrics with spatially adaptive modeling to generate a localized understanding of ecological vulnerability. The results reinforce the notion that fragmentation does not manifest uniformly and that specific patches carry more ecological significance and are more sensitive to anthropogenic pressures. With urbanization accelerating, there is an urgent need for spatially responsive forest governance strategies that account for ecological functionality, human well-being, and landscape resilience. By offering spatially explicit insights, this research supports more informed, context-sensitive conservation planning; protecting not just the forest cover, but the multifaceted ecosystem services and values that forests provide to current and future generations.

CONCLUSION

This study investigated the impacts of forest fragmentation on two key ecosystem services, water provisioning and recreational value, within the rapidly urbanizing Petaling District across three temporal benchmarks: 2005, 2014, and 2023. Utilizing supervised classification and landscape metrics, the findings revealed a clear trajectory of increasing fragmentation, particularly between 2005 and 2014, followed by partial recovery in forest cover by 2023. Structural changes in forest configuration were effectively captured through landscape metrics such as patch size, edge density, and connectivity, each offering distinct yet complementary insights into the spatial dimensions of fragmentation. The application of Geographically Weighted Regression (GWR) further enriched the analysis by uncovering spatial heterogeneity in the relationships between forest fragmentation and ecosystem services. Specifically, GWR highlighted non-stationary spatial relationships between landscape structure and proximity to both water bodies and urbanized areas. These spatially varying patterns underscore that the ecological consequences of fragmentation are not uniformly distributed but instead manifest differently across the landscape, depending on local conditions and spatial context. Collectively, the results emphasize the importance of incorporating fine-scale, spatially explicit data into urban planning and forest management frameworks. As development pressures intensify, particularly in urbanizing regions like the Petaling District, such data is essential for safeguarding ecological function and ensuring that ecosystem services continue to support human well-being. The study's findings call for a shift in environmental governance: from reactive, crisis-driven responses to proactive, anticipatory planning that is grounded not only in scientific evidence but also in a moral commitment to protecting the continuity and integrity of natural landscapes. This approach is vital for sustaining ecological resilience in the face of accelerating urban expansion.

This study provides details of the spatial forest fragmentation and its effects on ecosystem services through simplified proximity-based proxies for water provisioning and recreational value. Future work shall improve these proxies by applying more comprehensive models, such as the InVEST model, to illustrate better the different aspects of ecosystem services. However, this paper presents an in-depth analysis showing high spatial heterogeneity of forest fragmentation in Petaling District that can be translated into practical action plans on urban forestry management despite this inadequacy. The study directly responded to the research gap stated in the introduction concerning the incapability of global statistical models to articulate spatial heterogeneity in ecological processes by applying Geographically Weighted Regression (GWR) and disclosing an empirically stationary relationship between metrics of forest fragmentation and ecosystem services across space global models cannot provide such information through this localized modeling approach the study demonstrated how impacts of fragmentation differ across the Petaling landscape towards a more sensitive context understanding of dynamics on ecosystem services spatial econometrics with landscape metrics delivered as a methodological new insight for assessment on urban forest resilience within fast growing tropical city regions. Overall, the results highlight a spatially adaptive analytical approach between urban and ecology studies. Thus, landscape configuration links the performance of specific sites concerning ecosystem services to provide concrete actions for planners and policymakers who want to balance urban development with ecological sustainability. This paper discusses how environmental management can be an entry point into the discourses of forest governance and attempts at perpetuating ecosystem services in Southeast Asia through bridging spatial analysis.

CONFLICT OF INTEREST

The authors declare that they have no competing interests.

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