Spatial Insights into Mangrove Ecosystem Services in Perak, Malaysia: A Preliminary Assessment Using Satellite Imagery

Muhammad Akmal Roslani [1,2*], Mohd Hasmadi Ismail[1*] and Norizah Kamaruddin[1,3]

[1]Faculty of Forestry and Environment, Universiti Putra Malaysia, 43400 UPM, Serdang, Selangor, Malaysia

[2]Faculty of Applied Sciences, Universiti Teknologi MARA, Perlis Branch, Arau Campus, 02600 Arau, Perlis, Malaysia

[3]Institute of Tropical Forestry and Forest Products, Universiti Putra Malaysia, 43400, UPM Serdang, Selangor, Malaysia

*mhasmadi@upm.edu.my, m.akmalroslani@gmail.com

Abstract: *Mangrove ecosystems are critical to coastal resilience, biodiversity conservation, and human livelihoods. They provide a range of ecosystem services (ES), such as flood protection, carbon storage, nutrient cycling, and support for fisheries. However, assessing and mapping these services on a broad landscape scale remains challenging, particularly in regions with limited data availability. This study presents a preliminary assessment of the potential supply of mangrove ecosystem services (MES) in Tanjung Burung and Matang, Perak, Malaysia, primarily designated forest reserves. Using SPOT-6 satellite imagery and a Land Use Land Cover (LULC)-MES matrix approach, we classified seven LULC classes. We analyzed their spatial contribution to 29 identified key MES subservices. Expert surveys were conducted to gather qualitative insights and quantitative estimations of MES potential supply, covering provisioning, regulating and maintaining, and cultural services. The preliminary analysis revealed that cultural services resulted in the highest mean scores for their potential capacities of MES supply compared to the regulating and maintenance, and provisioning services. Mangroves emerged as the most multifunctional land cover, achieving the high potential capacities of MES supply across all 29 assessed MES subservices, outperforming other classes. A spatial visualization of these services was generated, offering a clearer understanding of their distribution and intensity across the landscape. The result highlights the value of remote sensing as a scalable tool for MES assessment, especially in data-scarce contexts.*

Keywords: Mangrove Ecosystem Services, Ecosystem Service Mapping, SPOT-6 Imagery, Land Use Land Cover Matrix, Sustainable Mangrove Management.

Introduction

Mangroves are unique ecosystems that thrive along the tropical and subtropical coasts of estuaries, bays, and lagoons. They are consisting of salt-tolerant woody plants (Avtar et al., 2017; Martínez-Espinosa et al., 2020). About 28% of the world's 150,000 km² of coverage is in Southeast Asia (Swangjang & Panishkan, 2021). In regions like Malaysia, these ecosystems act as ecological buffers by protecting coastal communities from flooding and supporting fisheries and local economic activity (Kanniah et al., 2015). The ecosystem services (ES) framework, which is being utilized increasingly in managing natural resources, focuses on the tangible and intangible benefits mangroves contribute to human well-being (Sannigrahi et al., 2019).

Nevertheless, despite their significance, global mangrove ecosystems are experiencing decline primarily due to unsustainable human activities and the impacts of climate change (Lee et al., 2022). Aquaculture, oil palm development, and urbanization cause deterioration in Southeast Asia, notably in Malaysia, where unsustainable land reclamation worsens ecological decline (Lee et al., 2022; Quevedo, 2023). A contributing factor to the ongoing degradation of mangrove ecosystems is the inadequate comprehension of the value of mangrove ES, leading to their exclusion from public decision-making and policy making (Lee et al. 2022). Despite their high monetary value, many mangroves ES are excluded from formal economic markets and are often undervalued in national accounting systems because many of these services have characteristics of public goods (Brander et al., 2012). Long-term socio-ecological resilience is threatened when local communities and policymakers overlook their benefits. Lack of participative or expert-based valuation approaches has led to limits their effectiveness in influencing decision making for policy or management (Lee et al., 2022). Despite these characteristics, private incentives to sustainably manage mangrove ES are limited and markets for them do not exist (Brander et al., 2012). Therefore, recent research emphasizes the necessity for multi-stakeholder valuing processes that combine ecological data, community perspectives, and socio-economic outcomes (Lee et al., 2022). Without this integration, ES breakdown and social vulnerabilities will escalate.

Traditional ES assessments often overlook spatial dynamics essential to ecosystem planning. Remote sensing (RS) makes visualizing ES distribution in resource-limited tropical locations cost-effective. This spatialized strategy is crucial for mangrove ecosystems because urban growth and aquaculture threaten multifunctional functions. Despite upland forest mapping advancements, mangrove ES remains poorly understood in Southeast Asia (Getzner & Islam, 2020). Thus, this study utilizes satellite data and "matrix-based" approach analysis to fill this gap. Overall, mapping ES in mangroves involves identifying, quantifying, and valuing the benefits provided by mangrove ecosystems to humans and the environment (Bherwani et al., 2025).

This study assesses spatially mangrove ES in Perak, Malaysia. SPOT-6 (*Satellite pour l'Observation de la Terre*) satellite imagery and an expert-informed land use/land cover (LULC)–mangrove ecosystem services (MES) matrix is employed to address data gaps in non-monetary mangrove value and spatial planning. The core objectives of this study are as follows: (1) classify and map dominant LULC types; (2) construct a LULC–MES matrix to quantify potential ES supply; (3) visualize spatial MES patterns using GIS-based analysis; and (4) demonstrate MES contributions to relevant SDGs. Expert-derived scoring indicates mangrove ES across landscapes, whereas high-resolution SPOT-6 data provide substantial granularity for coastal LULC categorization. It aligns with global ecosystem accounting frameworks (UN, 2021) and Sustainable Development Goals (SDGs) which is increasingly supported in the literature (Mathai et al., 2023; Jia et al., 2023). The findings will advance evidence-based mangrove conservation policy, financial planning, and mainstream management practices in local, national, and regional sustainability strategies agendas.

Literature Review

Mangroves are unique intertidal ecosystems comprised of salt-tolerant trees and shrubs thriving along tropical and subtropical coastlines, particularly between latitudes 25–30° north and south (Avtar et al., 2017). Mangroves, which cover only 0.7% of tropical forests, provide significant ecological and socioeconomic benefits, including nutrient cycling, carbon storage, coastline protection, and fishery support. These services are driven by structural complexity, including tree species diversity, canopy density, and dynamic sediment processes (Azman et al., 2021; Worthington et al., 2020). They are undervalued in mainstream resource management. Understanding their ecological function improves ecosystem resilience and required for better mangrove management and conservation strategies (Ashton et al., 2003). Integrating mangrove ES into national accounting and conservation frameworks requires a systems-based understanding of mangrove functionality.

The concept of ES has evolved significantly since the 1970s. ES has gained global traction through programmes like the Millennium Ecosystem Assessment (MEA, 2005), which proposed the now-standard classification of provisioning, regulating, cultural, and supporting services. This approach stressed how ecosystems support humankind. The Economics of Ecosystems and Biodiversity (TEEB) (2010) mainstreamed the economic worth of these services. They advocated for their adoption into national accounting systems. The Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) introduced the Nature's Contributions to People (NCP) framework, which addresses local and Indigenous viewpoints and embraces diverse knowledge systems (Díaz et al., 2015).

These changes underscore the necessity to link ecosystems to policy tools. The Common International Classification of Ecosystem Services (CICES) is notable for its designed spatial and land-use integration. Decision-making and sustainability planning benefit from its compatibility with satellite data and ecosystem accounting frameworks like SEEA-EA (Haines-Young & Potschin, 2018). The assessment of ES has emerged as an essential tool in scientific literature and mapping approaches, including the intricate characteristics of ES into environmental management and decision-making (Mathai et al., 2023).

Remote sensing and Earth observation may assist us in comprehending and managing mangrove ecosystems and their critical services to the environment and human beings (Roslani et al. 2024). These technologies have transformed mangrove ES monitoring and assessment across spatial and temporal scales. Freely available imagery from satellites such as Landsat-8 and Sentinel-2 with medium spatial resolution (30 and 10 m) are commonly employed for data extraction from extensive mangrove forests (Mahdavifard et al., 2023). The availability of very-high-resolution satellite sensors has created enhanced opportunities for mapping mangrove land cover compared to earlier sensors, such as SPOT-6 imagery (Oktorini et al., 2021). The utilization of satellite data with a finer spatial resolution has the potential to identify smaller patches of forests, thereby yielding more detailed mangrove extent maps that are capable of monitoring areas that have been previously omitted (Liu et al., 2021). SPOT-6's 1.5 m panchromatic and 6 m multispectral resolution allows precise mangrove ES mapping for spatially explicit policy interventions and local ecosystem-based management strategies. Oktorini et al. (2021) have demonstrated better spectral separability and overall accuracy of SPOT-6 imagery in mangrove land cover classification compared to RapidEye imagery. This study combines SPOT-6 data with a "matrix-based" approach named LULC–MES matrix approach for site-specific service assessment beyond conventional proxies. The integrated approach improves mapping precision and remote sensing's decision-support role in climate resilience and coastal governance.

The Land Use/Land Cover-Ecosystem Services (LULC–ES) or matrix assessment, first proposed by Burkhard et al. (2009), remains extensively utilized and flexible for assessing ES potentials, particularly in data-scarce or complicated contexts like mangrove ecosystems. Expert-based scoring links land cover classifications to ES categories, enabling qualitative but structured evaluations of provisioning, regulating, and cultural services. Unlike monetary valuation methods, the matrix-based model integrates context-specific ecological functions and community dependencies, making it more relevant and applicable (Kankam et al., 2022; Mathai et al., 2023). This emphasizes the significance of transdisciplinary collaboration and the necessity of integrating knowledge and data from a variety of sources and stakeholders, including economists, political scientists, communication specialists, and natural scientists (Lee et al., 2022). Despite its simplicity, the matrix-based assessment supports spatial planning, conservation, and sustainable land-use policy. The present study employs the matrix assessment and high-resolution spatial datasets to quantify mangrove ES locally policy-relevantly. Thus, in order to facilitate sustainable land use management, it is essential to conduct spatially explicit assessments of the potential for ES (Perennes et al., 2020).

This non-monetary method for valuing ES is effective in data-scarce contexts like mangrove ecosystems. This flexible paradigm for evaluating provisioning, regulating and maintenance, and cultural services uses expert knowledge and land cover typologies instead of financial proxies, which often overlook context-sensitive values. For instance, Mathai et al. (2023) mapped 16 mangrove-related ES in Ungwana Bay, Kenya, using satellite imagery and a LULC matrix approach to capture high-value regulating and cultural services often overlooked in economic models. Similarly, research in Ghana and Italy has leveraged this method to reflect temporal ES changes and local socio-ecological dynamics (Gaglio et al., 2016; Kankam et al., 2022). In addition to enhancing knowledge sharing, recent methods of ES mapping also involve stakeholders in the modelling process (Campagne & Roche, 2018), which enhances legitimacy and emphasizes the ES that are most significant in a specific context (Owuor et al., 2024). Despite expanding global use, Southeast Asia, especially Malaysia, lacks comprehensive studies combining expert-informed matrix scoring with high-resolution satellite data. Addressing this gap could lead to better grounded, spatially explicit, and policy-relevant mangrove ES assessments.

Mangrove ecosystem services (MES) are increasingly recognized for their vital roles in climate regulation, food security, biodiversity protection, and cultural identity, aligning with multiple Sustainable Development Goals (SDGs), including SDG 13 (Climate Action), SDG 14 (Life Below Water), and SDG 1 (No Poverty). Sustainable development (SD) refers to the utilization of natural resources in a manner that does not compromise the fundamental needs of future generations and aims to attain balance among environmental, economic, and social dimensions (Eyzaguirre et al., 2023). This study spatially maps fine-scale mangrove ES subservices and links them to SDGs to fill that gap. The Sustainable Development Goals (SDGs) have motivated nations globally to attain a more equitable and sustainable future

(Bimrah et al., 2022). Such mapping reveals mangrove contributions that typical valuation approaches overlooked. Recent research emphasizes the urgency of linking ecological services to practical development goals (Bimrah et al., 2022; Eyzaguirre et al., 2023). This study's innovation is converting MES into policy-relevant formats for national planning and community resilience. This research enhances our comprehension of mangroves as ecological assets and socio-political tools for sustainable development by capturing MES's multiple values.

Methodology

a. Study Area:

This research examines mangrove zones on Perak's western coast, primarily in Tanjung Burung Forest Reserve and Matang Mangrove Forest Reserve (MMFR) near Sungai Tinggi (Figure 1), mostly designated as forest reserves. Malaysia's flagship mangrove reserve, the MMFR, spans 40,466 ha in Perak, excluding key waterways.

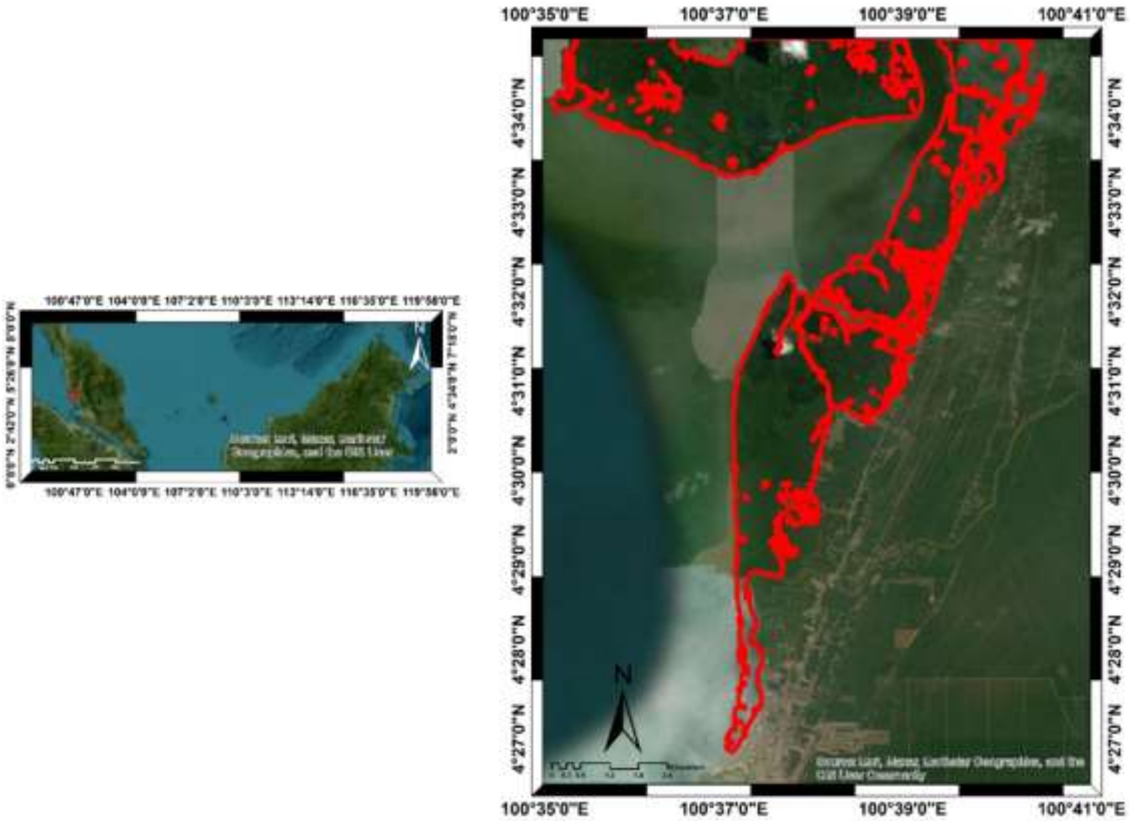

Figure 1: Map of the study site of the mangrove area in Perak, Malaysia.
(Source: ESRI, 2025)

Tanjung Burung Forest Reserve, a 1,079-hectare mangrove forest on Malaysia's west coast in Perak's Kinta/Manjung district, has been gazetted since 1903. It borders Pantai Remis, a local fishing and tourism hub, and supports nearby communities' environment and economy (Fuazi et al., 2022). Tanjung Burung is a small, underdocumented, and underrepresented mangrove reserve. We anchor our spatial analysis on two well-managed and less-documented mangrove areas to highlight the MES potential contrast and guide future conservation planning across Perak's mangrove landscape.

b. Data Sources and Acquisition:

High-resolution SPOT-6 satellite imagery has proven instrumental in accurately mapping and monitoring mangrove ecosystems, offering superior spectral separability and classification accuracy compared to other sensors like RapidEye or Landsat. SPOT-6 is a commercial Earth observation satellite owned and operated by Airbus Defence and Space acquires panchromatic imagery at 1.5-meter (m) spatial resolution and multispectral imagery (blue: 450–525 nm, green: 530–590 nm, red: 625–695 nm, near-infrared: 760–890 nm) at 6 m resolution, with a swath width of 60 kilometers (km) and a daily revisit capability when both satellites operate in tandem (Oktorini et al., 2021). This satellite imagery data was acquired in August 2023 from the Malaysian Space Agency (MYSA).

c. Image Pre-Processing

To ensure the accuracy and reliability of satellite-based analysis, SPOT-6 imagery underwent a structured pre-processing workflow. This began with radiometric and geometric corrections to address sensor distortions and ensure spatial alignment to a standard coordinate system (Oktorini et al., 2021). Cloud masking was then applied to eliminate atmospheric interference, followed by band stacking to integrate all multispectral layers into a single composite image. This process enhanced the spectral depth required for robust land use/land cover (LULC) classification. The resulting dataset provided a uniform spectral signature across the study area, facilitating more consistent classification outputs. The pre-processing was conducted using a hybrid platform approach, leveraging the analytical strengths of ERDAS Imagine and ArcGIS. This integration ensured compatibility with GIS-based analyses and spatial modelling of MES, setting the foundation for precise LULC classification and downstream mapping of MES.

d. Land Use / Land Cover (LULC) Classification

In this study, LULC classification was performed using the Support Vector Machine (SVM) algorithm within the ArcGIS environment, chosen for its strong performance in complex and heterogeneous ecosystems such as mangroves. SVM is a machine learning technique effective in addressing non-linear classifications in high-dimensional spaces and can offer superior accuracy relative to other machine learning methods (Rosmasita et al., 2019). High-resolution SPOT-6 images and ground-truth field surveys identified seven land cover types: intact mangrove, non-mangrove vegetation, mangrove logged/cleared area, coastal area, built-up area, water body, and barren land. The classification process began with digitizing training samples and applying SVM, effectively distinguishing subtle spectral variances among land covers. Confusion matrices provide a comprehensive method for assessing classifier performance, which is crucial for data science (Sathyanarayanan & Tantri, 2024). In addition, the Kappa approach is often employed to assess overall accuracy and the ratio of accurately categorized pixels (Feizizadeh et al., 2022). This demonstrates SVM's robustness, especially when integrated with high-resolution imagery, offering superior thematic precision compared to traditional methods. However, a gap persists in embedding SVM outputs into ES frameworks. This study addresses a fundamental methodological convergence between remote sensing and ES science, enabling spatially nuanced and policy-relevant MES assessments. SVM together with SPOT-6 data provides a reproducible, cost-effective, and scalable model for tropical coastal regions, especially in data-limited environments.

e. Identification of Mangrove Ecosystem Services

This study conducted a literature-based review in regional biogeographic and socio-ecological contexts to identify Perak's applicable MES subservices. We systematically analyzed peer-reviewed MES studies in similar situations to extract provisioning, regulating, and cultural services based on a literature review (Afonso et al., 2021). Instead of using global frameworks without adaptation, the final services list is environmentally meaningful and locally applicable. Based on the CICES structure, we identified 29 MES subservices. We evaluated and refined them through a structured survey of local "mangrove experts" (academics, government, non-government sector, researchers, ecologists, etc.) familiar with the local landscape. Survey responses were collected in the field and online, which helped confirm which MES occur or hold significance in the study area. This hybrid approach bridges scientific evidence and realities on the ground, enhancing credibility and stakeholder buy-in. The novelty lies in merging expert-informed, literature-anchored sub-services with spatial mapping workflows, which is a scarce approach in Southeast Asian mangrove research, and creating a personalised MES inventory is innovative. The method provides an excellent basis for spatially explicit MES assessment in policy-oriented landscapes by anchoring valuing in local ecological knowledge and global science.

f. Development of the LULC-MES Matrix

The matrix-based approach established by Burkhard et al. (2009) assesses MES potential supply across LULC class types. Namely, the LULC-MES matrix model was used in this study. This approach integrates expert evaluations to associate land cover classifications with MES and to map and assess nature's benefits across landscapes for enhanced planning and environmental decision-making (Burkhard et al., 2009). Based on the Common International Classification of Ecosystem Services (CICES), this study aligns with recent attempts to improve categorisation rigour and cross-scale applicability (Czúcz et al., 2018). The MES assessment was undertaken through a semi-structured expert elicitation process with 31 selected experts regards to their ecological expertise and mangrove system experience in this study region. Based on their knowledge and the local context, each expert scored the potential supply capacities of LULC types across the MES subservices on a 0–5 Likert scale: 0= no potential supply, 1= very low, 2= low, 3= medium, 4= high, and 5= very high potential supply. In line with MES assessment best practices, focused expert selection improves context-specific accuracy and avoids generalisation errors in large-scale randomised surveys (Sieber et al., 2021a; Sieber et al., 2021b). Using mean values to aggregate scores evaluates service potential and allows spatial display of MES distribution. The methodological innovation of this study lies in integrating structured expert knowledge with LULC-based spatial mapping in data-scarce mangrove ecosystems.

f. Spatial Integration and Potential Supply of MES Mapping

Expert-derived mean scores were incorporated into the categorised LULC map using a polygon-based relational join in ArcGIS to represent MES potential supply spatially. Based on CICES, each polygon was assigned scores for provisioning, regulating and maintenance, and cultural services. This method produced three thematic layers of MES maps by symbolising LULC polygons by score. We created a composite map to locate multifunctional service hotspots and low-supply locations. This spatial integration enhances service distribution understanding and conservation zoning (Perennes et al., 2020; Sieber et al., 2021a; Sieber et al., 2021b; Wangai et al., 2018) especially in ecologically vulnerable mangrove environments. This method strengthens MES visualisation with expert knowledge and spatial analytics for more informed, localised, and scalable planning.

Results and Discussion

a. Land Use/Land Cover (LULC) Classification Output

The seven main LULC types were mangrove, non-mangrove, mangrove logged/clear area, coastal area, built-up, water body, and bare land produced after supervised satellite imagery classification (Figure 2). The final classification scored 91.88% accuracy and a Kappa coefficient of 0.9010, proving its trustworthiness and alignment with ground-truth and high-resolution Google Earth data. The classification result showed that non-mangrove areas made up 35% of the study area's classification image, including agriculture (palm oil, rubber, etc.), horticulture, fruit orchard, land forest, grassland, mixed, and other vegetations in the study area are classified as non-mangrove. Water body (including oceans, tidal channels, creeks, lagoons, shallow ponds, aquaculture ponds, rivers, lakes, etc.) was the second highest proportion (28%). The third largest proportion resulted 18% of the classification result, was intact mangrove class which areas of unique coastal ecosystems with trees and shrubs nearly solely that are species almost exclusively found in mangrove environments. Then followed by coastal area (11%) with mudflats, sandy places, etc. within the research area. Classification results below 10% include built-up (5%) (including buildings, roads, utilities, residential, commercial, and industrial features), bare land (2%) specifically are referring to those non-vegetated patches whether naturally occurring or due to disturbances and lastly mangrove-logged/cleared areas represent a specific class within mangrove ecosystem that distinguishes zones where the original, intact mangrove forest has been substantially disturbed by human activities (e.g.; deforestation, logging activities etc.) or natural phenomena (e.g.; erosion) made up at only 1%.

The classification outcomes from this study affirm the robustness of SPOT-6 imagery, when coupled with the SVM classifier, in effectively delineating diverse LULC types within these mangrove ecosystems. The high spatial resolution of SPOT-6 enhances its ability to capture fine-scale variations across land cover classes, including mangrove subtypes, non-vegetated surfaces, and anthropogenically modified zones. The ability of SVM to manage high-dimensional datasets and its resilience to overfitting make it particularly well-suited for high-resolution optical satellite imagery. Unlike conventional classifiers like Maximum Likelihood Classification (MLC) or Decision Trees, SVM stands out due to its ability to handle high-dimensional data and deliver accurate results even with limited training samples (Mahdavifard et al., 2023; Fu et al., 2022). SVM demonstrates strong spectral discrimination capabilities, enabling accurate separation of closely related classes. These results underscore the synergy of SPOT-6 data and SVM methodology in producing reliable, scalable, and transferable LULC maps essential for supporting spatial MES assessments and evidence-based coastal management strategies.

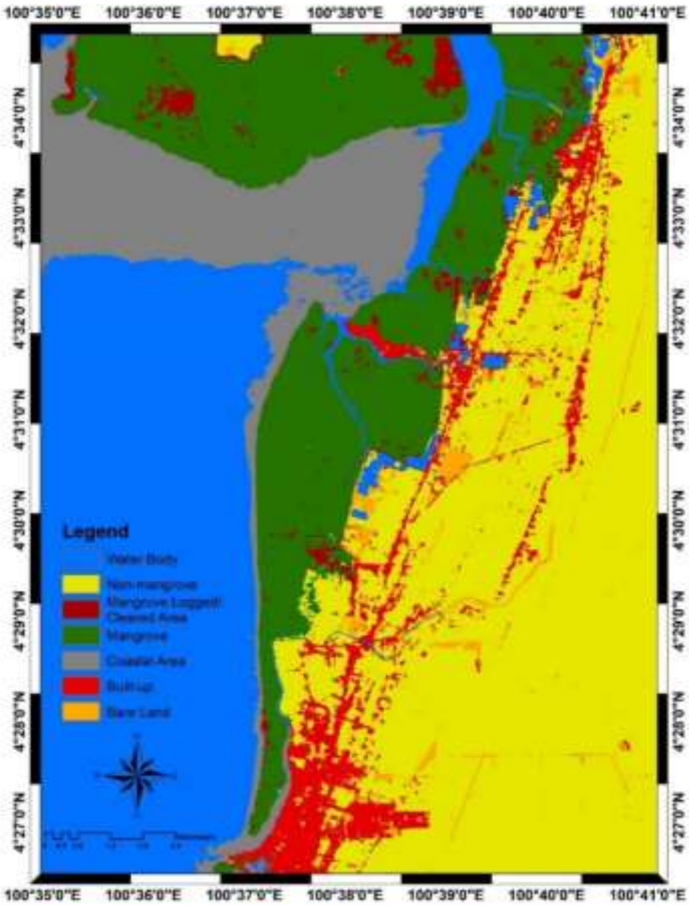

Figure 2: LULC classification of each class present within the study site of the mangrove area in Perak, Malaysia was processed using SPOT-6 satellite image sensed in August 2023.

b. Expert-Derived LULC–MES Matrix Scoring

The LULC-MES matrix evaluates 29 MES subservices in seven LULC classes. The expert-based LULC–MES matrix (Table 1) synthesises scores from 31 specialists and experts from various government and non-government sectors, such as forestry, academia, researchers, etc. Scores range from 0 (no potential supply) to 5 (very high potential supply), facilitating a comparative evaluation of each land cover's multifunctionality. The LULC-MES matrix shows that intact mangrove has the highest MES mean score of all LULC types. Mangrove habitats were the most versatile LULC class, outperforming all other classes across all MES subservices with mean scores of 3 to 5. This is not surprising since mangroves are keystone ecosystems in tropical and subtropical coastal zones that provide important ES.

Provisioning services provide food, materials, energy, other resources, and employment opportunities. Mangroves had the greatest average provisioning value of 3.9 among all LULC classes, highlighting their importance to local livelihoods. However, the barren land class contributed the least, scoring 1.3 on average. Among individual services, local employment had the highest mean score at 3.3, slightly higher than fisheries food resources at 2.9. Timber resources contributed less, with a mean score of 2.0, indicating resource scarcity and possible extraction or availability limits.

Table 1: Matrix of the assessment of the different LULC classes' capacities to supply selected MES within the study area (LULC-MES matrix).

LULC CLASSES	PROVISIONING SERVICES										REGULATING AND MAINTENANCE SERVICES															CULTURAL SERVICES			
	Food resources (Fisheries)	Food resources (Wild food)	Materials (Wood products)	Materials (Timber)	Energy resources (Charcoal)	Energy resources (Firewood)	Materials (Fodder)	Pharmaceutical resources	Genetic resources	Local employment	Climate regulation (Carbon sequestration)	Coastal protection	Erosion control	Flood control	Water quality regulation	Water purification	Bioremediation	Sediment trapping	Nursery and breeding ground	Habitat for species	Nutrient cycling	Soil formation and composition	Primary production	Biodiversity	Biological control	Education and research	Recreation and tourism	Aesthetic value	Cultural Heritage and social relation value
Mangrove	4	4	4	4	4	4	3	3	4	4	4	5	5	4	4	4	4	4	4	4	4	4	4	4	4	5	4	4	4
Non-mangrove	3	3	3	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Mangrove Logged/Cleared Area	3	2	3	3	3	3	2	2	2	3	3	2	3	3	3	2	2	3	3	3	3	3	3	3	3	3	3	3	3
Coastal Area	4	3	2	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	4	3	3	3	3	3	4	4	4	3
Built-up	1	2	1	1	1	1	1	1	1	3	2	2	2	2	2	2	1	2	2	2	1	2	2	2	2	3	3	3	3
Water Body	4	3	1	1	1	1	2	2	3	4	4	3	3	3	3	3	3	3	4	4	4	3	3	4	4	4	4	3	4
Bare Land	1	1	1	1	1	1	1	1	1	2	2	2	2	2	1	1	1	2	1	2	2	2	2	2	2	2	2	2	2

Note: The different colour of the following capacities of MES potential supply explained as the assessment scale as follows; 0= rosy colour (no potential supply), 1= grey green (very low potential supply), 2= light green (low potential supply), 3= yellow green (medium potential supply), 4= blue green (high potential supply), and 5= dark green (very high potential supply).

Regulating and maintenance services involve 15 essential MES subservices. Mangroves again provided the greatest average value across these subservices with a mean score of 4.3, highlighting their importance in ecological balance. Built-up and bare land classes performed worst, each scoring 1.6, indicating their inadequate environmental capability. Habitat for species and biodiversity had the highest average scores of 3.0 for individual services. Meanwhile, bioremediation had the lowest mean score of 2.5, the least represented regulating and maintenance services.

According to a substantial literature review, cultural services fall into four categories. Again, mangroves contributed the most, with a mean score of 4.3, indicating their cultural, educational, and recreational significance. In comparison, bare land had the lowest cultural benefit score of 1.8. Scores ranging from 3.0 to 3.3 were fairly consistent across all four categories when assessing individual services. Education, research, recreation, and tourism were the highest valued, scoring 3.3, highlighting mangroves' importance in learning and leisure. While significant, 'aesthetic value' scored the lowest at 3.0, suggesting visual and experience enjoyment may be more subjective or location dependent.

Overall findings showed that cultural services resulted the highest overall mean score (3.2) of the three MES studied, followed by regulating and maintenance (2.8) and provisioning services (2.4). Cultural services indicate deep and enduring human-mangrove ecological interactions but are typically neglected or difficult to quantify. These include opportunities for education, recreation, aesthetic enjoyment, and the preservation of cultural heritage. In many coastal areas, mangroves function as 'living classrooms,' promoting environmental education and scientific discovery that foster ecological awareness among both residents and visitors (Treviño, 2022). Ecotourism, nature-based excursions, and community research boost local economies and conservation (Faubiany et al., 2024). Thus, equitable and inclusive mangrove governance requires participatory and culturally sensitive CES integration into coastal planning (Himes-Cornell et al., 2018). Our findings support a previous study showing accessible fringe mangrove areas in Perak are cultural hotspots that sustain community well-being and eco-cultural tourism.

Mangrove forests are the most critical land cover class for MES in LULC, scoring 4.2 across all 29 assessed services. This highlights their importance in climate regulation, shoreline stabilisation, and biodiversity (Brander et al., 2012). Structural complexity and environmental heterogeneity in mangrove root systems affect fish diversity in which the pneumatophores and prop-roots of these forests provide shelter and food for fish species, especially juveniles (Nagelkerken et al., 2008). Mangroves are vital ecosystems that significantly contribute to coastal fisheries in Malaysia by providing food, refuge, and nursery grounds for marine organisms (Chong, 2007). In addition to food, mangroves provide materials and energy. Nagelkerken et al. (2008) also have summarized that mangrove wood is employed for construction, fuel, and crafts such as mangrove timber, which is renowned for its durability and resistance to rot thus it is an optimal choice for coastal structures, including boats and residences. In addition, local energy is also generated through the use of charcoal and firewood derived from mangrove wood. Mangroves' biotic diversity offers unexplored pharmacological and genetic opportunities for bioprospecting and climate-adaptive agriculture (Alongi, 2014). Many coastal communities also depend on fishing, ecotourism, and non-timber forest products (NTFPs) harvesting for the economic backbone (Mukherjee et al., 2014).

c. Spatial Distribution of Mangrove Ecosystem Services (MES)

The regional distribution of MES illustrates ES and the dynamic human-nature relationship. This study used satellite imagery classified LULC and MES matrix assessment to create spatially explicit maps of provisioning, regulating and maintenance, and cultural services. The LULC-MES matrix means scores (Table 1) and the LULC classification map of the research area have been employed to create theme layers to depict MES's potential spatial supply capacities across the landscape. The maps in Figure 3 (a, b, c) illustrate clear spatial heterogeneity in service distribution by LULC class. Provisioning services focus on accessible mangrove fringes, whereas regulating services encompass entire and continuous mangrove patches. Cultural services, however, are confined and occur in places with human, infrastructure, or ecotourism potential. Mapping these services ensures that resource extraction is balanced with conservation efforts (Bherwani et al., 2025).

Mangrove resulted high potential supply capacities across all provisioning MES. These forests were identified as key providers of food and materials essential for the livelihoods of coastal villagers (Owuor et al., 2024). Fisheries, wild food, timber, and fuelwood were highest in dense mangrove stands, especially along estuarine and deltaic zones, according to spatial modelling of intact mangrove class provisioning services. Food and raw material production is one of nature's most essential services and one of the most mapped in ES assessments (Rovai et al., 2023). These forest regions, mostly near river mouths and community access points, show substantial human dependency, supporting earlier findings that accessibility heavily influences resource usage (Walters et al., 2008;). Fishing is vital to this community's economy and livelihoods (Fuazi et al., 2022). Kiso and Mahyam (2003), have summarized that the Matang estuary is a vital nursery environment that supports fisheries and related activities. Study conducted by Yue et al. (2025) towards local communities around Matang Mangrove Forest Reserve also stated that mangrove ecosystems are vital fishing grounds for 56% of respondents, with small-scale fishermen harvesting fish, shrimp, crabs, and other marine organisms. However, human-modified landscapes like barren land had little provisioning capacity, resulting in low potential supply capacities for all 29 MES subservices.

Mangroves' vast canopies and dense, interconnected root systems gave them high potential supply capacities for regulating and maintenance services. These forests protect against erosion and reduce wave energy due to their dense root systems that are tangled up to trap sediment and anchor soil, also their above-ground structures which absorb and dissipate wave force which resulting in reducing their storm surge and tide impact to prevent erosion from strong currents or human activity (Bherwani et al., 2025). In addition, Mahdavifard et al. (2023) also noted that these ecosystems protect inland areas and prevent coastal floods and erosion. Ismail et al. (2017) found that the mixed mangrove forest of *Rhizophora* and *Bruguiera* species in Matang, Perak, is highly effective in reducing wave height, with the first 10 meters being the most impactful thus, highlights the importance of mangroves in coastal protection and their role in mitigating wave energy. These findings show that mangroves are essential to coastal resilience and ecosystem-based disaster risk reduction. However, built-up and bare land areas, where vegetation fragmentation and canal construction have disrupted natural processes, showed a significant decline in regulating and maintenance service capacity. These findings emphasize the necessity of keeping intact mangrove belts to preserve ecological resilience and safeguard vulnerable coastal populations from mounting climate risks. Furthermore, spatial modelling helps identify precious sites for conservation, restoration, and integrated coastal zone management.

Cultural MES are intangible and underrepresented in spatial assessments. This study mapped cultural MES around ecotourism, educational, and scenic coastal locations. In all four MES subservices, mangrove, coastal area, and water body have substantial supply capacities. Accessible mangrove parks and boardwalks offer enjoyment, environmental education, and aesthetic appreciation, reflecting high cultural service ideals. Well-integrated infrastructure can boost cultural benefits and environmental awareness, making CES mapping crucial for inclusive and socially grounded coastal development. Through ecotourism, mangrove habitats provide cultural services like firefly-watching in Sepetang, where *Pteroptyx tener* bioluminescence offers unique visual and recreational pleasures. Fireflies depend on mangrove assemblages, especially *Sonneratia caseolaris*, which support their habitat. Wan Juliana et al. (2012) noted that mangrove vegetation directly affects firefly populations, which sustains and attracts firefly-based tourism in this culturally and economically vital coastal region. Islam et al. (2024) also emphasizes that mangrove ecotourism contributes significantly to Malaysia's economy, with activities like bird watching, kayaking, and wildlife observation.

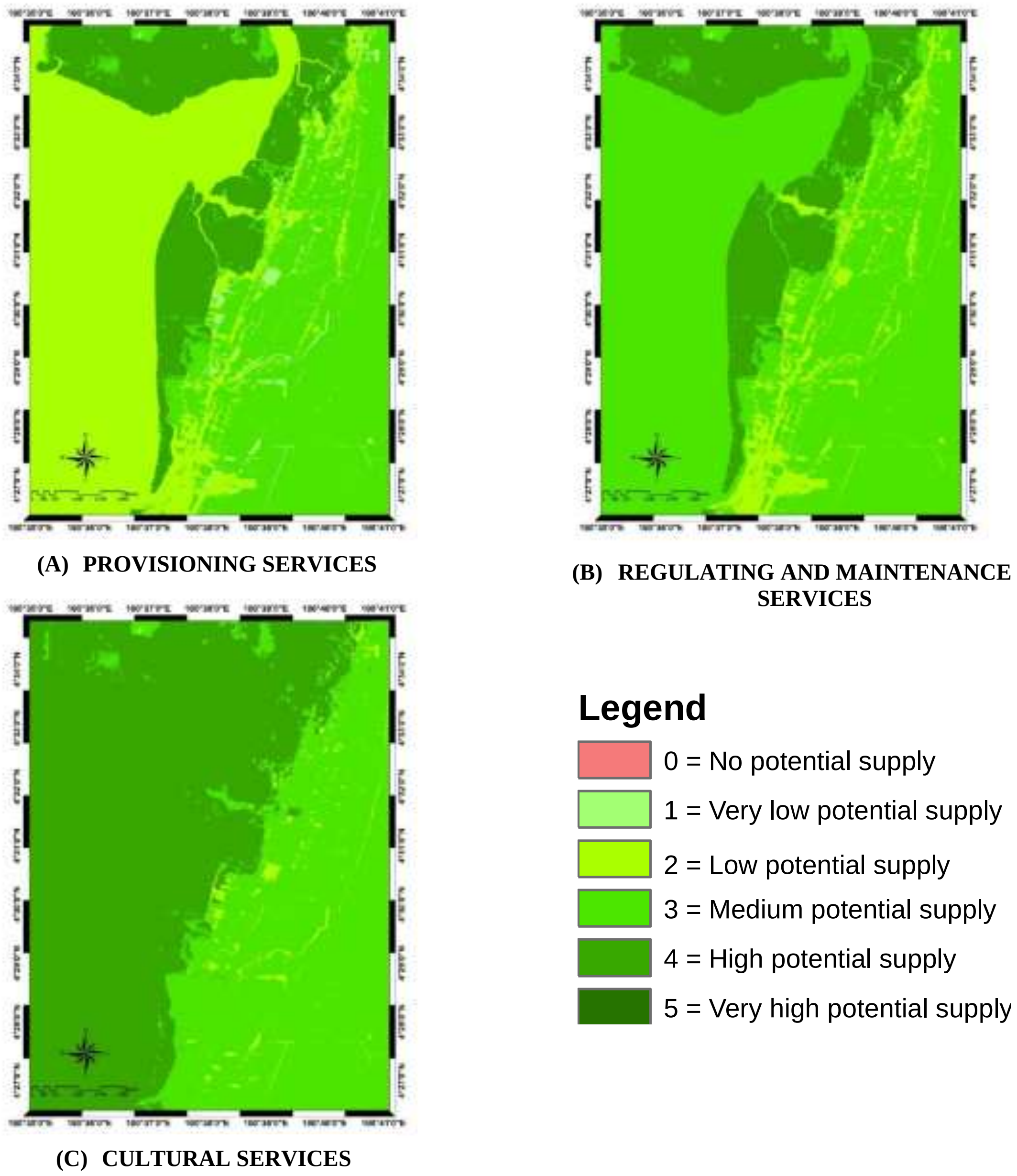

Figure 3: The spatial distribution of potential supply of MES for (A) provisioning, (B) regulating and maintenance, and (C) cultural services provided in the study site of the mangrove area in Perak, Malaysia.

SPOT-6 satellite imagery and GIS analysis show that MES are distributed differently across LULC classes, with mangroves constantly appearing as multifunctional "hotspot" zones. Intact mangrove ecosystems provide overlapping provisioning, regulating, and cultural services, demonstrating their ecological and societal significance (Castillo et al., 2017; Sievers et al., 2023). Functionally significant LULC types, such as mangroves, are identified using matrix-based assessments. In contrast, spatial models show where and how services are delivered. This dual approach provides a powerful foundation for studying biophysical and anthropogenic MES allocation drivers. ES maps offer as crucial instruments for decision-makers and institutions, allowing for the spatial identification of regions that should be preserved due to their significant provision of ES and its sustainability (Martinez-Harms & Balvanera, 2012). Moreover, the data obtained from mapping ES can inform policymakers about the importance of mangroves and the need for regulations to protect them (Bherwani et al., 2025).

d. Mangrove Ecosystem Services (MES) Contributions of Mangroves to the UN Sustainable Development Goals (SDGs)

Mapping identified MES against the United Nations Sustainable Development Goals (SDGs) reveals their diverse significance in sustainability. Mangroves' ecological, economic, and cultural functions were highlighted by 29 MES subservices that coincide with 13 of 17 SDGs (Figure 4). Bimrah et al. (2022) also in their study found that mangrove ES contribute to 13 relevant SDGs in a disproportional way.

Figure 4: Mangrove Ecosystem Services (MES) Aligned with the Relevant United Nations Sustainable Development Goals (SDGs)

Regulating services, like carbon sequestration, coastal protection, and biodiversity support SDG 13 (Climate Action), SDG 14 (Life Below Water), and SDG 15 (Life on Land). In the context of reducing coastal flood risk, mangroves possess specific characteristics that affect wave attenuation inside the forest, including their dense above ground canopy and unique, resilient root system that diminishes water flow and disperses wave energy thus, substantially mitigate the risk of flooding in low-lying coastal areas (Sunkur et al., 2023). In terms of carbon sequestration, mangroves are among well-known blue carbon ecosystems with the most carbon-rich ecosystems. The study conducted by Ismail et al. (2015) highlights the potential of mangrove forests in Kuala Sepetang to sequester and store significant amounts of atmospheric carbon, emphasizing their role in global carbon budgets and climate change mitigation through their ability to act as efficient "blue carbon" sinks. Fisheries, wild food, and timber promote SDGs 1 (No Poverty), 2 (Zero Hunger), and 8 (Decent Work). Fishing and related activities are the primary source of income for the majority of people residing in or near mangrove forest areas (Walters et al., 2008). Moreover, although the direct harvest of mangrove wood and plants is rarely a full-time occupation for them, a significant number of them rely on these products to meet their subsistence requirements for fuel and construction materials while, for others, the harvest and sale of mangrove forest products serve as a significant supplement to their income (Walters et al., 2008). Recreation, education, and heritage are mostly related to SDGs 4 and 17. This is because, known as the "nurseries of the sea," mangroves are unique coastal ecosystems that support diverse marine life thus, mangrove ecotourism may improve ecosystems by exhibiting their natural beauty and providing a dynamic platform for environmental education and experiential learning (Verawati & Al Idrus, 2023).

This SDG-MES mapping turns MES into policy-relevant indicators and highlights mangroves' strategic relevance in ecosystem-based planning. The findings indicate that incorporating with ES frameworks improves decision-making, blended finance, and national sustainability reporting. Mangroves are essential to resilient, equitable, and sustainable development and ecological buffers. Conservation strategies and efforts ought to be a priority for environmental and human security.

Conclusion and Recommendation

The SPOT-6 imagery and Support Vector Machine (SVM) classifier supervised classification identified seven key land use/land cover (LULC) classes with 91.88% accuracy and a Kappa coefficient of 0.9010, proving model robustness. Non-mangrove areas accounted for the most extensive coverage (35%), followed by water bodies (28%) and intact mangroves (18%). Coastal area, built-up, bare land and mangrove logged/clear area were also identified through the image classification. The SVM's ability to manage non-linear class borders and spectral overlap helped distinguish closely related LULC classes. At the same time, SPOT-6's high spatial resolution allowed detailed mapping of mangrove ecosystems. SVM performed better in mangrove and coastal classification in various high-impact studies. The most multifunctional land cover was mangroves, scoring 4.2 across all 29 MES subservices. Due to their ecological and socioeconomic importance, they outperformed other classes in provisioning, regulating, maintaining, and cultural services. Mangroves are important in education, tourism, and heritage, as cultural services scored the highest mean (3.2) compared to other main services. This highlights the necessity for inclusive, knowledge-driven mangrove governance and conservation because mangroves sustain worldwide biodiversity, livelihoods, and climate resilience. Integration of LULC and MES matrix scoring allowed high-resolution mangrove ecosystem services (MES) mapping, revealing different geographical patterns across provisioning, regulating and maintenance, and cultural services. MES hotspots aligned with intact mangroves, highlighting their diverse functions and importance to coastal resilience and livelihoods. Provisioning, regulating, and cultural services were focused on accessible mangroves, dense canopies, and ecotourism zones. This integrative approach promotes evidence-based coastal planning and adaptive conservation under development pressures. The mangrove ecosystems potentially promote 13 of 17 UN Sustainable Development Goals (SDGs) by providing varied MES. Regulations like carbon sequestration and coastal protection directly support SDGs 13, 14, and 15 in this research of 29 subservices. Fisheries and timber enhance food security and local livelihoods, addressing SDGs 1, 2, and 8. Cultural services support SDGs 4 and 17 through education and heritage. MES improves national reporting, ecosystem-based planning, and equitable, climate-resilient development in SDGs frameworks.

This study suggests frequent sustainable mangrove ecosystem management strategies. First, coastal planning using MES maps assists in prioritising mangrove area protection and restoration, especially in high-value zones. As national assets, mangroves may contribute to achieving numerous SDGs, including climate action, food security, and biodiversity. Mangroves are socially and culturally important, thus governance ought to be community-driven. In order to support conservation, blue carbon credits and Payments for Ecosystem Services (PES) should be increased. Education and ecotourism infrastructure should be improved to boost environmental awareness and economic resilience. Finally, monitoring with expert-based MES assessments and satellite data is cost-effective and scalable.

These initiatives might preserve mangroves as ecosystems and underpinnings for sustainable and equitable coastal development.

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