From Horizontal to Vertical Urban Growth: A Decade of LULC Change in Penang Island, Malaysia

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Abstract

Urban growth is conventionally defined by spatial expansion and the increase in built-up areas. This study, however, reveals a counterintuitive trend in Penang Island, Malaysia, between 2014 and 2023. Utilising 1.5 m pansharpened SPOT 6 and SPOT 7 satellite imagery classified with a Support Vector Machine (SVM), we analysed spatiotemporal changes in land use and land cover (LULC). Our findings indicate a decline in built-up areas, a stark contrast to the official Department of Statistics Malaysia (DOSM) figures, which show a significant increase in population. This paradox challenges traditional urbanisation patterns, necessitating a more in-depth examination of the underlying spatial, spectral, and socio-economic dynamics. We explore several plausible explanations: vertical urban densification through high-rise development, urban redevelopment cycles involving temporary demolition, and policy-driven land-use conversions towards green infrastructure for enhanced liveability and climate resilience. Furthermore, technical limitations in remote sensing, such as spectral occlusion from dense vegetation or shadows, were identified as potential contributors to classification errors, validated through fieldwork and ground truthing. These findings highlight the critical need for a multidimensional understanding of urbanisation, moving beyond mere horizontal expansion to encompass vertical growth, redevelopment lag, spatial constraints, and policy-driven transformations. This analysis is situated within the context of Sustainable Development Goal 11 (SDG 11), Malaysia's National Physical Plan (NPP) Thrust 2, the New Urban Agenda (NUA), and the Malaysia Urban Observatory (MUO) which advocates for a more holistic approach to sustainable urban development.

Keywords: LULC change, remote sensing, vertical urban growth, densification, sustainable development

Introduction

Rapid urbanisation often converts natural landscapes into built environments, influencing local climate, biodiversity, and ecosystem services (Burkhard et al., 2012). In many Southeast Asian cities, including those in Malaysia, this process has been characterised by horizontal expansion at the expense of agricultural and vegetated land (Chakraborty & Joshi, 2020). Urbanisation entails the intense consumption of land, energy, and natural resources to sustain expanding populations and economic activities. While this growth brings about greater human services such as housing, infrastructure, and employment opportunities, it often degrades ecosystem services that support environmental balance and human well-being. The extent and quality of these ecosystem services are closely linked to the spatial distribution and configuration of land use and land cover (LULC).

Penang Island is no exception to this trend, as it continues to experience significant demographic and spatial changes associated with rapid urban development. According to the Department of Statistics Malaysia (DOSM, 2023), Penang Island's population increased from 722,384 in 2014 to about 830,000 in 2023, representing around fifteen percent growth over the decade. Hence, this study aims to quantify the LULC change between 2014 until 2023 in Penang Island, Malaysia. The focus is on understanding how population growth, urban policies, and land management strategies collectively influence the built-up areas. The findings provide insight into how spatial planning supports sustainable development and demonstrate that urban contraction, often seen as decline, can represent progress toward ecological balance and long-term urban resilience.

Literature Review

a. Land Use and Land Cover (LULC) Change and Urban Dynamics

LULC analysis has become an essential tool in understanding the spatial dynamics of urbanisation and its environmental implications. The conversion of natural and agricultural areas into built-up land is widely regarded as one of the most visible indicators of anthropogenic pressure on ecosystems (Burkhard et al., 2012; Seto et al., 2012). Rapid urbanisation, particularly in developing regions, often leads to extensive sprawl, resulting in fragmented landscapes, biodiversity loss, and reduced ecosystem service provision (Abdullah & Nakagoshi, 2007). Traditional urban growth studies have therefore focused primarily on measuring the extent of built-up expansion and its correlation with population increase and economic activity.

However, recent scholarship suggests that urban growth does not always equate to spatial expansion. In mature or highly constrained cities, growth may occur through intensification, redevelopment, and verticalisation, leading to complex land transitions that cannot be captured solely through two-dimensional mapping (Abdelsalam et al., 2019). Such shifts challenge the conventional understanding of urban sprawl and necessitate a more nuanced analysis of urban morphology and function.

b. Emerging Trends: Vertical Densification and Urban Contraction

The emergence of vertical urbanism represents a paradigm shift in city development, particularly in areas with geographical or policy-induced spatial limitations. According to Chen et al. (2020), Wang et al. (2025), and Piętocha et al. (2025), vertical densification, which is defined as the increase in building height and volume within existing footprints reflects an adaptive response to land scarcity and sustainable planning principles. This transformation reduces pressure on peripheral zones while promoting infrastructure efficiency and mixed land use.

Urban contraction, meanwhile, refers to a decrease in the areal extent of built-up land without necessarily indicating urban decline. This phenomenon can occur due to redevelopment cycles, temporary demolition for reconstruction, or policy-enforced greening initiatives. Studies in Asian cities such as Singapore and Seoul show similar trends where horizontal shrinkage is offset by an upward concentration of population and infrastructure (Abdelsalam et al., 2019). In Penang's context, such a pattern aligns with government efforts to balance urban efficiency with environmental sustainability.

DOSM (2023) data further supports this transition, indicating that despite steady population growth, residential density within the Northeast District increased from 5,400 persons/km^2 in 2014 to over 6,300 persons/km^2 in 2023, reflecting intensification rather than outward expansion. This aligns with observed redevelopment cycles and policy-driven infill strategies designed to optimise land use under the Penang Structure Plan (2020–2030).

c. Remote Sensing and Machine Learning in Urban Change Detection

The advancement of remote sensing technologies has enabled detailed LULC monitoring across multiple spatial and temporal scales. High-resolution imagery from sensors such as SPOT 6 and SPOT 7 offers significant advantages for urban analysis, allowing differentiation of fine-scale land-use categories and structural patterns. The application of machine learning algorithms, particularly the Support Vector Machine (SVM) classifier, has proven effective for complex urban environments due to its robustness in handling heterogeneous data and limited training samples (Mountrakis et al., 2011; Khatami et al., 2016).

d. The Challenge of Spectral Occlusion in Vertical Cities

One of the primary challenges in urban remote sensing is spectral occlusion, that is the partial or complete shadowing of features caused by tall structures, vegetation, or topography (Khatami et al., 2016). In dense urban areas, vertical development alters the spectral characteristics of the surface, resulting in underestimation of built-up areas in 2D classifications (Lu et al., 2004). Reflective surfaces, building shadows, and mixed pixels contribute to classification uncertainty, especially when distinguishing between impervious surfaces and adjacent vegetation.

Penang Island's topography, with its coastal plains and central hilly terrain, amplifies this issue. Tall buildings in George Town and Bayan Lepas create shadow zones that obscure rooftops and pavements, while vegetated slopes in the central spine complicate the delineation of agricultural and forested areas. Studies in other compact cities, such as Hong Kong and Kuala Lumpur, have shown that integrating LiDAR or Digital Surface Models (DSM) can substantially improve built-up detection accuracy by capturing the vertical dimension of urban form (Abdelsalam et al., 2019). These techniques provide complementary data that can overcome spectral occlusion and improve the interpretation of multi-temporal change.

e. Policy Context: SDG 11, NPP Thrust 2, the NUA, and the MUO

The observed shift in Penang's urban pattern from horizontal expansion to vertical densification corresponds with broader sustainability frameworks. The Sustainable Development Goal 11 (SDG 11) aims to make cities inclusive, safe, resilient, and sustainable by promoting compact urban forms, efficient resource use, and reduced ecological footprints (United Nations, 2015). Similarly, the New Urban Agenda (NUA) emphasises integrated spatial planning and compact city strategies to mitigate uncontrolled sprawl and improve land-use efficiency.

At the national level, Malaysia's National Physical Plan (NPP) Thrust 2 explicitly advocates for sustainable urbanisation through land optimisation and ecosystem preservation (PLANMalaysia, 2021, 2023). The plan supports the intensification of existing urban areas, protection of environmentally sensitive zones, and promotion of mixed-use development. In Penang, these principles are operationalised through the Penang Structure Plan (2020–2030) and the Penang

Green Agenda, both of which encourage high-density redevelopment while maintaining ecological corridors and green belts.

Empirical research in Penang indicates that policy interventions have influenced the island's spatial trajectory. For instance, the relocation of industrial activities to the Southwest District and the introduction of heritage conservation zoning in George Town have collectively slowed horizontal expansion. The integration of such policy considerations into spatial analyses is crucial for interpreting observed LULC changes as more than just technical outputs; they reflect deliberate planning strategies that align with national and global sustainability commitments.

f. Research Gap and Contribution

Although numerous studies have investigated LULC change in Penang and other Malaysian cities, most have concentrated on urban expansion rather than contraction or vertical restructuring. Few have examined the implications of spectral occlusion and temporal redevelopment on the perceived shrinkage of built-up areas. Moreover, most existing studies adopt purely spatial or statistical approaches, lacking the integrative perspective that connects land-use dynamics with sustainability policies.

This study contributes to filling that gap by interpreting the apparent contraction of built-up land in the context of vertical densification, redevelopment, and policy transformation, and second is to situate Penang's experience within the frameworks of SDG 11, NUA, and NPP Thrust 2. By doing so, it advances the discourse on sustainable urban transitions and underscores the need for multidimensional urban monitoring that integrates spatial, spectral, and policy-based insights.

Methodology

a. Study Area

Penang Island is located on the northwest coast of Peninsular Malaysia and covers approximately 293 square kilometres. It consists of two main administrative districts: the Northeast District, which contains the island's urban and commercial core, and the Southwest District, which remains relatively rural with agricultural and forested landscapes. The island's coastal and inland zones exhibit varying degrees of development intensity, making it a suitable site for studying spatial changes in urban land use patterns (PLANMalaysia, 2023). Figure 1 shows the area of Penang Island, Malaysia.

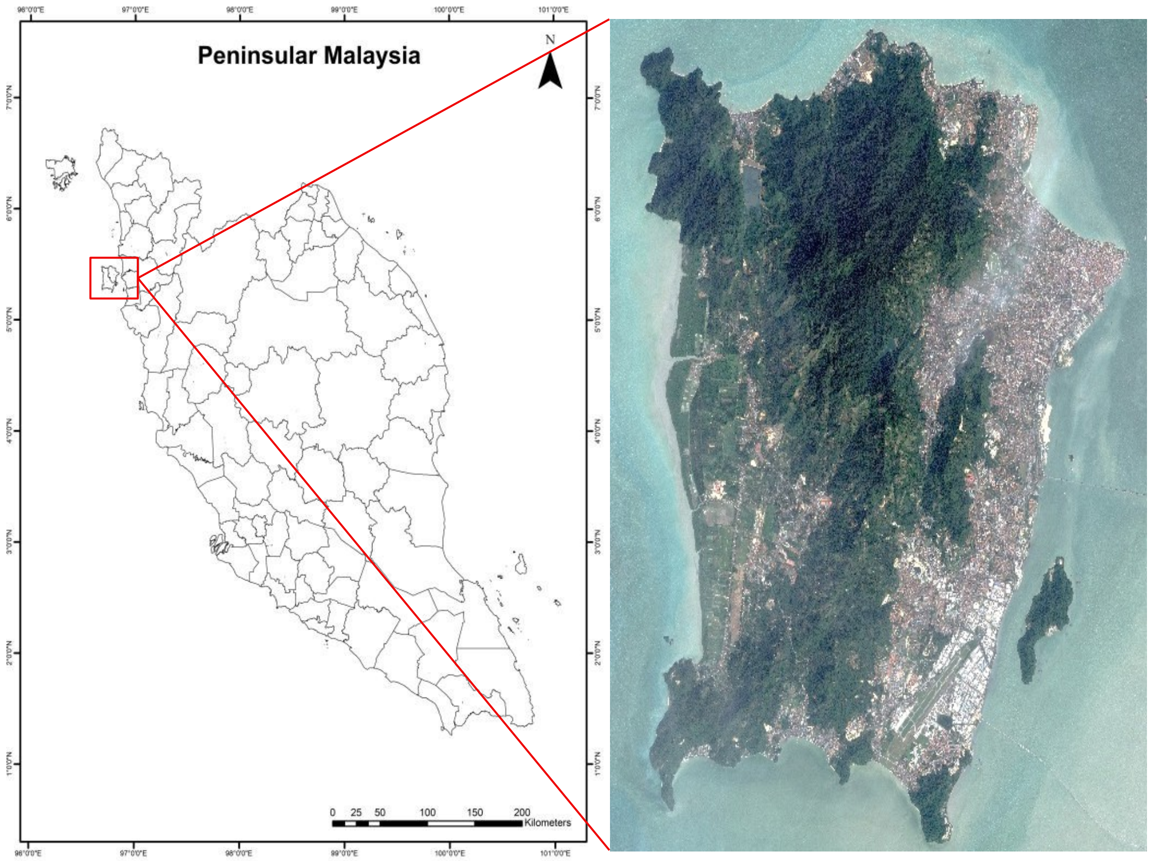

Figure 1: Map of Penang Island, Malaysia

b. Datasets and Preprocessing

This study utilised satellite imagery from SPOT 6 (2014) and SPOT 7 (2023), both acquired from the Malaysian Space Agency (MYSA). The images were delivered in JPEG 2000 (JP2) format with lossless compression, maintaining full spectral quality and a spatial resolution of 1.5 metres. Preprocessing procedures included radiometric and geometric corrections to ensure consistency and alignment between the two datasets (MYSA, 2023).

Complementary vector datasets were provided by PLANMalaysia Penang, which included administrative boundaries, road networks, and land use zoning layers. The original land use dataset contained twelve categories, which were reclassified into five major LULC classes that are built-up, vegetation, agriculture, forest, and water bodies to align with the classification results from SPOT imagery and maintain comparability (PLANMalaysia, 2023).

c. Image Classification

Supervised classification was conducted using the Support Vector Machine (SVM) algorithm due to its robustness in handling complex urban spectral signatures and limited training data (Chakraborty & Joshi, 2020). The SVM classifier works by constructing an optimal separating hyperplane that maximises the margin between different land use categories in the feature space. Training samples were selected using stratified random sampling to ensure representative coverage of all classes.

Accuracy assessment was carried out using a confusion matrix derived from reference points and ground truth data. The overall accuracies achieved were 90.8 percent for 2014 and 94.2 percent for 2023, with Kappa coefficients of 0.85 and 0.90, respectively. These accuracy levels indicate that the classified maps were reliable for detailed spatial analysis, aligning with accuracy benchmarks reported in similar urban land studies.

d. Accuracy Assessment

Accuracy assessment was conducted to evaluate the reliability of the LULC classification for 2014 and 2023, following standard approaches widely applied in remote sensing studies (Congalton, 1991; Foody, 2002). A total of 500 reference points were selected using stratified random sampling, ensuring proper representation across built-up areas, forests, water bodies, agricultural and horticultural areas, and barren land.

The classification's accuracy was sequentially evaluated using a Confusion Matrix, which compared the classified map with the ground truth data. For accessible areas, 200 ground truth points were systematically collected during field visits to ensure reliable validation. For areas that were inaccessible due to terrain or restricted entry, 300 points were carefully interpreted using high-resolution imagery from Google Earth Pro as a reference source.

Key accuracy metrics, including overall accuracy, producer's accuracy, user's accuracy, and the Kappa coefficient, were calculated to quantify the classification's performance. This comprehensive assessment ensured that the LULC classification was reliable and suitable for use in land management and environmental monitoring applications. Table 1 and Table 2 present the Confusion Matrix computed for the years 2014 and 2023, respectively.

Table 1: Confusion Matrix for 2014 LULC Classification

Class	Built-up	Forest	Water Bodies	Agriculture and Horticulture	Barren Land	Total	User's Accuracy	Kappa
Built-up	82	1	0	3	1	87	0.942	0
Forest	0	274	0	5	0	279	0.982	0
Water Bodies	0	1	7	0	1	9	0.777	0
Agriculture and Horticulture	1	23	2	64	0	90	0.711	0
Barren Land	8	0	0	0	27	35	0.771	0
Total	91	299	9	72	29	500	0	0
Producer's Accuracy	0.901	0.916	0.777	0.888	0.931	0	0.908	0
Kappa	0	0	0	0	0	0	0	0.847

The 2014 LULC classification matrix presents strong classification performance in several categories, with an overall accuracy of 90.8% and a Kappa coefficient of 0.847. The built-up and forest classes show high reliability, with User's Accuracies of 94.25% and 98.21% respectively, indicating that most pixels classified as built-up and forest were indeed correct. Producer's Accuracies for these classes are also high, at 90.11% for built-up and 91.64% for forest, suggesting that the model effectively captured most actual built-up and forest areas. The water bodies class, while achieving a producer's accuracy of 77.78%, struggled with the same user's accuracy at 77.78%. Agriculture and horticulture had moderate accuracy, with 88.89% Producer's Accuracy and 71.11% User's Accuracy. Barren land performed reasonably well, with Producer's Accuracy of 93.1% and User's Accuracy of 77.14%, reflecting relatively accurate identification.

Table 2: Confusion Matrix for 2023 LULC Classification

Class	Built-up	Forest	Water Bodies	Agriculture and Horticulture	Barren Land	Total	User's Accuracy	Kappa
Built-up	77	0	0	0	1	78	0.987	0
Forest	1	289	0	6	0	296	0.976	0
Water Bodies	0	0	9	0	0	9	1	0
Agriculture and Horticulture	6	9	0	83	3	101	0.821	0
Barren Land	3	0	0	0	13	16	0.812	0
Total	87	298	9	89	17	500	0	0

Producer's Accuracy	0.885	0.969	1	0.932	0.764	0	0.942	0
Kappa	0	0	0	0	0	0	0	0.900

The 2023 classification results yield the highest accuracy of all years, with an overall accuracy of 94.2% and a Kappa coefficient of 0.9, reflecting near-perfect agreement. Built-up and forest classes continued to show excellent accuracy, with User's Accuracies of 98.72% for built-up and 96.75% for forest, reflecting a high proportion of correct classifications for these key LULC. Producer's Accuracies were similarly high at 88.51% for built-up and 96.98% for forest. Water bodies achieved perfect classification in 2023, with both Users' and producers' accuracies at 100%, reflecting outstanding reliability in identifying this class. Whereas agriculture and horticulture showed substantial improvement with a User's Accuracy of 82.18% and a Producer's Accuracy of 93.26%, indicating that most classified pixels and actual areas for this class were correctly identified. Barren land also showed improvement, with a User's Accuracy of 81.25% and a Producer's Accuracy of 76.47%, though it remained slightly lower than other classes, indicating ongoing but improved classification performance. Thus, the results show consistent accuracy for built-up and forest classes across all years, with significant improvement in water bodies classification by 2023, as well as notable enhancements in agriculture and horticulture classification.

Results and Discussion

a. LULC Change from 2014 until 2023 in Penang Island

As shown in Table 3, the LULC of Penang Island in 2014 was primarily characterised by forested areas, covering 169.1 km^2, which represented 56.6% of the total area. Agricultural and horticultural lands were the second most extensive category, occupying 54.2 km^2 (18.2%), followed closely by built-up areas at 52.8 km^2 (17.7%). Barren land and water bodies were the least represented, covering 21.1 km^2 (7.1%) and 1.4 km^2 (0.5%), respectively.

The spatial distribution of LULC classes in 2014 reflects a landscape largely shaped by natural vegetation, with forests and agricultural areas dominating the land cover. This pattern highlights the island's ecological richness and the continued significance of primary land-based activities. Figure 4.2 geovisualizes the 2014 LULC of Penang Island, offering a clear snapshot of its land cover configuration.

By 2023, forested areas had decreased to 179.4 km², accounting for 59.6% of the total area, yet still dominating more than half of the island's landscape. Agricultural and horticultural areas expanded significantly to 62.7 km² (20.8%), indicating a growing shift toward land-based production. Built-up regions continued to decline, reaching 48.3 km² (16%), while barren land further reduced to 9.3 km² (3.1%). In contrast, the area of water bodies increased slightly to 1.6 km², covering 0.6% of the total area. Figure 4.4 shows the spatial distribution of LULC across Penang Island in 2023, reflecting the LULC transitions that occurred since 2019.

Table 3: LULC from 2014 until 2023 and Three Phases of Changes in Penang Island

LULC Type	2014		2023		Change Over 2014-2023 (Overall Change)	
	km^2	%	km^2	%	km^2	%
Built-up	52.8	17.7	48.3	16.0	-4.5	-1.7
Forest	169.1	56.6	179.4	59.5	10.3	2.9
Water Bodies	1.4	0.5	1.6	0.5	0.3	0.08
Agriculture and Horticulture	54.2	18.2	62.7	20.8	8.5	2.6
Barren Land	21.1	7.1	9.3	3.0	-11.8	-4.0

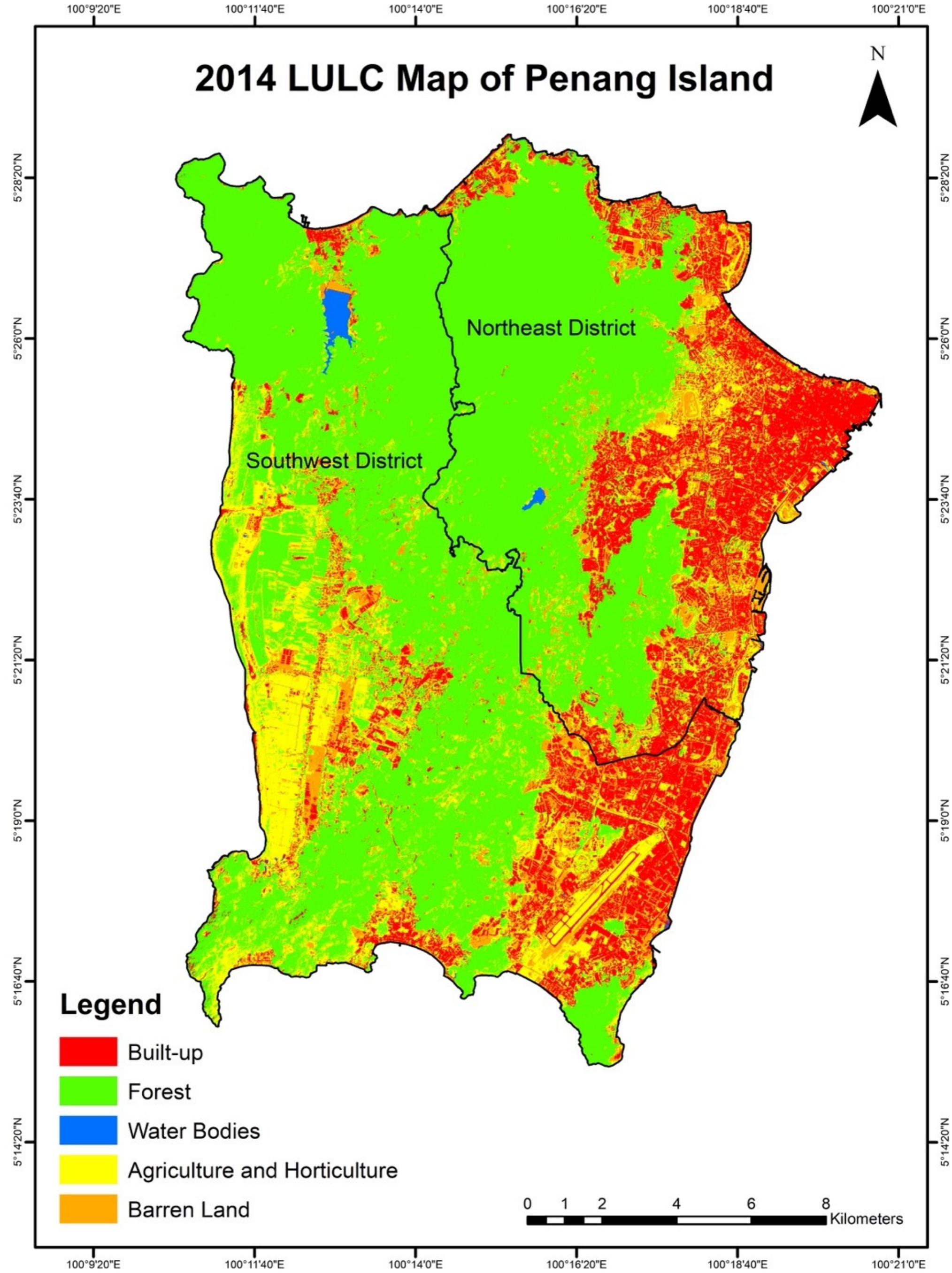

Figure 2: 2014 LULC Map of Penang Island

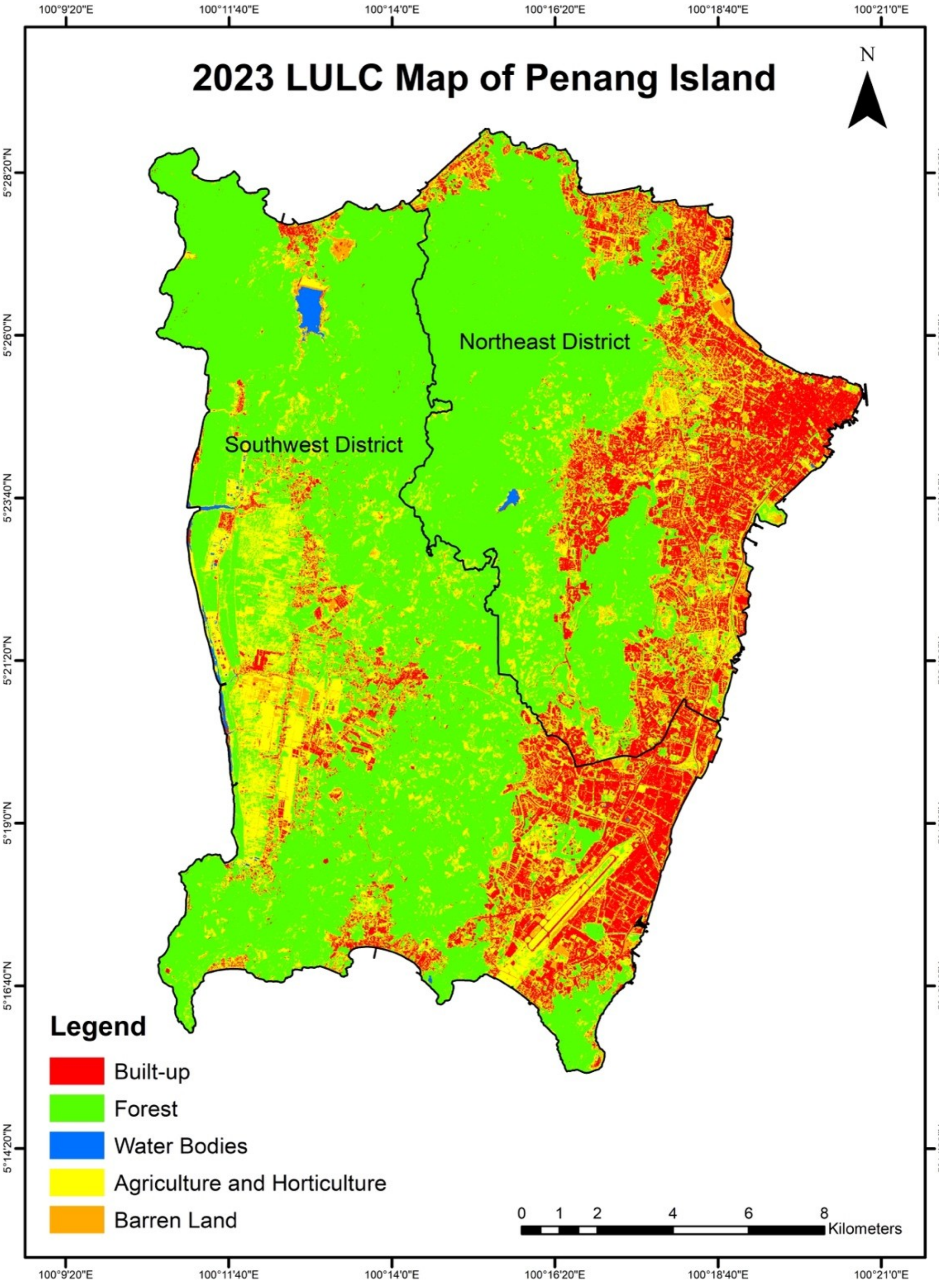

Figure 3: 2023 LULC Map of Penang Island

b. Discussion on the Changes in Built-Up Areas

The overall change from 2014 to 2023 revealed a decrease of about 4.5 km² (1.7%) in the built-up area on Penang Island. When analysed spatially, it was indicated no significant expansion of the built-up area or development in any specific direction, with urban growth remaining confined to existing boundaries. In other words, changes occur only internally. This observation aligns with the minor statistical changes observed over the past decade.

In this context, "changes take place internally" means that LULC reforms occur within existing built-up boundaries, rather than through outward urban expansion. This indicates that the city did not sprawl into new areas but restructured land uses internally, such as through redevelopment, infill projects, and vertical development. This trend reflects Penang's limited flat land, mountainous terrain, and land scarcity, which restrict horizontal growth. It also aligns with policies under NPP Thrust 2, which emphasise compact and efficient urban development to optimise land resources.

Spatially, urban development on Penang Island has largely remained confined within existing boundaries, with no significant outward expansion. The island's topography significantly influences this pattern, as nearly 50% of the land area is covered by mountainous terrain, limiting opportunities for horizontal growth. Consequently, built-up areas are concentrated in the Northeast District, particularly George Town, where the scarcity of available land and intense competition for space present major planning challenges. These constraints are further compounded by the fact that only 1.3% of the island's land remains allocated for open space and public use (Department of Statistics Malaysia, 2022).

The spatial concentration of built-up land in the Northeast District, particularly around George Town, reflects characteristics of the classical Concentric Zone Model (Burgess, 1925), where urban growth radiates outward from a central hub. However, Penang Island's expansion is constrained by its mountainous terrain, preventing extensive outward sprawl. Instead, elements of the Multiple Nuclei Model (Harris & Ullman, 1945) are also evident, with George Town serving as the administrative and commercial core, while Bayan Lepas functions as an industrial nucleus in the south. This suggests that Penang Island's urbanisation has evolved into a polycentric form, influenced by both economic specialisation and physical land constraints.

Before the adoption of the industrialisation policy in the 1970s, Penang was heavily forested, and its economy was primarily based on agriculture and regional trade. Since the 1970s, Penang has undergone rapid urbanisation, with its economy transitioning from a resource-based to a trading and manufacturing-focused one. A notable increase in built-up areas occurred from 1990 to 2005. As a result, Penang Island now faces challenges in expanding its urban areas without causing environmental damage or encroaching on agricultural and forested lands. Consequently, the rate of new built-up areas is slowing as the land supply dwindles, leading to the introduction of land reclamation and the growth of vertical development.

A comparison between Figure 2 and Figure 3 reveals that in ten years, the intense red shade representing the built-up area began to show yellow hues in between. This indicates the gradual infiltration of small patches of agricultural and horticultural land into the urban area. In other words, some areas of the built-up land have been supplemented by the presence of urban agriculture and horticulture.

As a result, the mixing of land uses led to classification ambiguities, which contributed to minor changes and a reduction in the recorded built-up area. This underlines that SPOT 6 and SPOT 7 were able to detect small changes and patches between the complex and complicated elements and structure of the pixels. As described by Airbus Defence & Space (2013), SPOT 6 and SPOT 7 products can be easily integrated into a GIS environment or used to derive thematic geoinformation.

From a technical standpoint, the observed decline may also be influenced by limitations in remote sensing, particularly spectral occlusion caused by cloud cover, haze, dense vegetation, or shadow effects, which can obscure built-up features during image acquisition. Importantly, this issue was validated through fieldwork and ground truthing, confirming that some urban regions were misrepresented or under-detected in the classified imagery due to these spectral interferences. Furthermore, spectral confusion between built-up land and visually similar surfaces, such as bare soil, construction zones, or transportation infrastructure, may have contributed to classification errors, underscoring the need for careful preprocessing and temporal cross-validation.

Figure 4 expounds the transition recorded in Table 4.4 into a map. It shows the changes in built-up areas in the Northeast and Southwest Districts between 2014 and 2023. The overall change observed between 2014 and 2023 shows a slight reduction in the built-up area on Penang Island. This suggests that the expansion of urban development has been counterbalanced by the presence of agricultural land within urban areas. If this trend persists, it could lead to a slowdown in urbanisation, promoting a more balanced and sustainable development pattern for Penang Island.

The post-classification comparison was applied to detect changes between 2014 and 2023. Classified maps from both years were overlaid in ArcGIS Pro 3.0 and ERDAS IMAGINE 2020 to produce a transition map, assessing the of changes of built-up.

The analysis primarily focused on the contraction of built-up areas, which was assessed by identifying pixels that transitioned from built-up land in 2014 to other categories in 2023. These were further verified using visual inspection of high-resolution imagery and reference datasets.

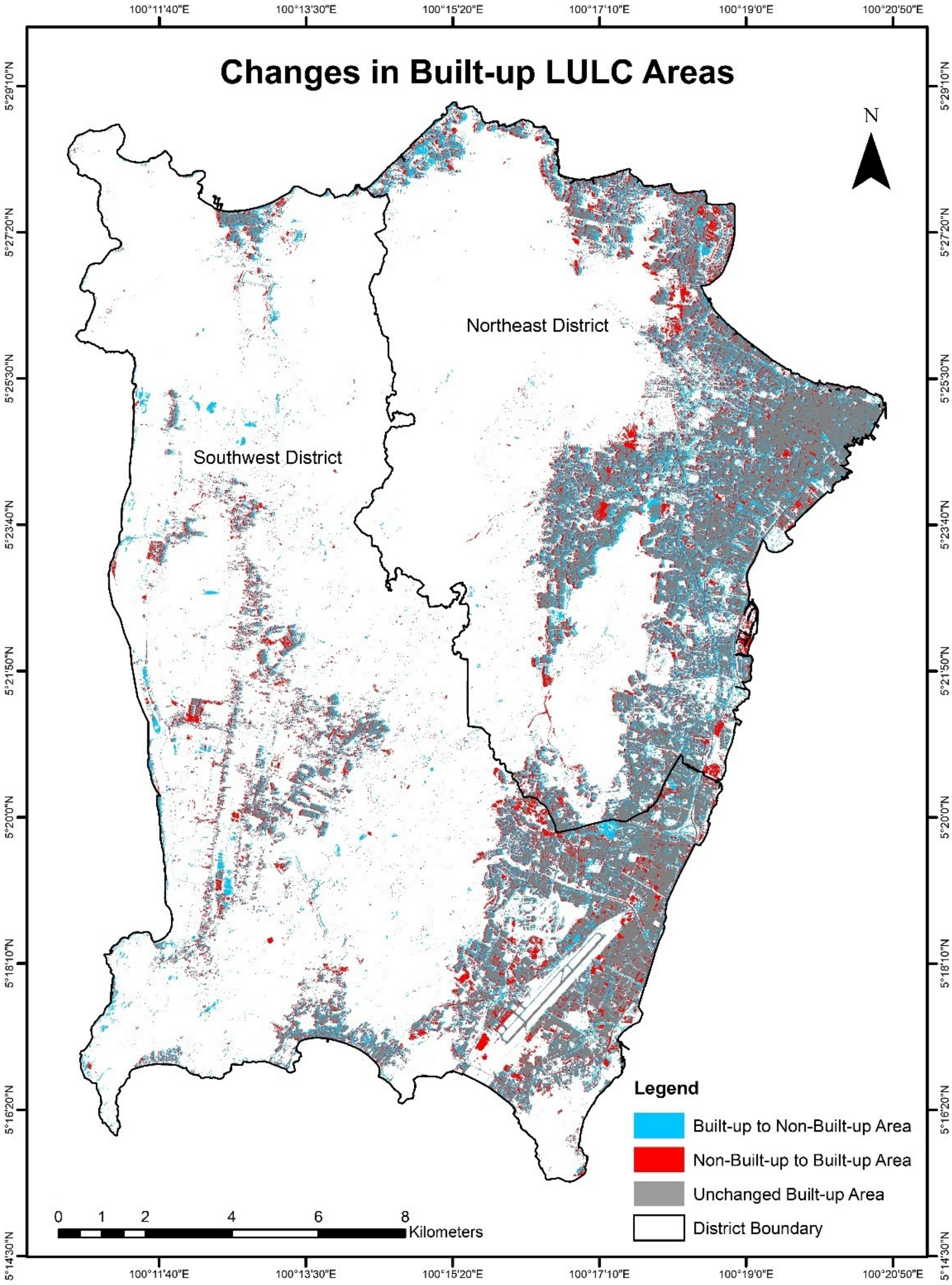

Figure 4: Changes in Built-up LULC Areas

c. Spatial Distribution and Ecosystem Implications

The contraction of built-up zones corresponded with regeneration of green cover in the island's western and central uplands. The forest class increased slightly, aided by reforestation and slope-stabilization projects, while agriculture resurged around Balik Pulau, supporting peri-urban food production. These spatial redistributions enhanced several regulating ecosystem services, including carbon storage, temperature moderation, and runoff control (Burkhard et al., 2012).

However, vertical urban growth introduced new ecological and microclimatic pressures. High-rise clusters increased impervious surfaces and surface albedo, intensifying localized heat islands. Meanwhile, limited ground-level open spaces constrained the delivery of cultural and recreational ecosystem services within dense cores. These findings reveal a complex trade-off: while horizontal shrinkage may yield landscape-scale ecological benefits, vertical intensification can concentrate environmental stressors (Abdelsalam et al., 2019).

d. Drivers of Change and Policy Context

The observed spatial reconfiguration reflects multiple interlinked drivers. The National Physical Plan (NPP) Thrust 2 promotes compact, resilient urban growth while restricting development in environmentally sensitive and high-risk areas (PLANMalaysia, 2021). Rising land values in the coastal plains have further encouraged redevelopment rather than outward expansion. Simultaneously, infrastructure improvements and land-use zoning revisions have incentivized infill and vertical renewal within established neighborhoods.

These policies align with Sustainable Development Goal 11 (SDG 11), which emphasizes inclusive and sustainable urbanization (United Nations, 2015). The Penang case demonstrates that spatial contraction of built-up areas, when guided by integrated planning, can coexist with economic dynamism and environmental recovery.

Conclusion and Recommendation

a. Conclusion

The decadal analysis of Penang Island's land use and land cover from 2014 to 2023 demonstrates a distinct transition from horizontal expansion to compact, vertically oriented urban development. Built-up areas exhibited measurable shrinkage, particularly in the Southwest District, while forest and agricultural zones showed moderate recovery. This spatial reconfiguration reflects both the geographical constraints of the island and the effectiveness of policy interventions such as the National Physical Plan (NPP) Thrust 2 and local zoning regulations that prioritize environmental protection and compact urban growth.

Despite high-resolution SPOT 6 and SPOT 7 imagery, spectral occlusion caused by shadows and vertical structures posed challenges in distinguishing built-up features, underscoring the need for complementary 3D and LiDAR-based analyses in future studies. Nonetheless, the results indicate that Penang Island is moving toward a sustainable urban form characterized by vertical densification, spatial efficiency, and partial ecological regeneration.

Importantly, the contraction of built-up areas should not be interpreted as urban decline but as evidence of urban restructuring, where redevelopment, land recycling, and green infrastructure contribute to balancing development with ecological resilience. These findings reaffirm that sustainable urban transitions can manifest not only through expansion control but also through strategic spatial shrinkage that enhances ecosystem functionality and aligns with Sustainable Development Goal 11.

b. Recommendations

1. **Integrate Vertical and 3D Urban Metrics:** Future LULC assessments should incorporate 3D spatial data, including LiDAR or digital surface models, to overcome spectral occlusion and accurately capture the extent of **vertical development** in compact cities.
2. **Continuous Monitoring Beyond 2023:** To evaluate the long-term sustainability of urban restructuring, subsequent monitoring using high-resolution multi-temporal imagery should be conducted at five-year intervals to assess post-2023 changes.

3. **Policy Reinforcement for Urban Regeneration:** The observed shrinkage of built-up areas offers a strategic opportunity for policymakers to reinforce urban regeneration frameworks—encouraging mixed-use, high-density developments that reduce land consumption while enhancing accessibility and sustainability.
4. **Community-Level Engagement:** Sustainable urban transformation requires the inclusion of community stakeholders in planning processes. Participatory mapping and local-scale feedback can ensure that redevelopment aligns with both environmental and social well-being.

In conclusion, Penang Island provides a compelling model for understanding urban transformation in constrained geographies. The findings highlight that sustainable urban futures are not defined solely by expansion, but by a balanced approach that harmonizes vertical growth, ecological restoration, and spatial equity.

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