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Combining GIS Data and Ground-Based Allometric Equations for Enhanced Carbon Stock Assessment

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Higher education institutions are crucial in addressing climate change by managing carbon emissions. While many universities focus on reducing their operational carbon footprint, more research must be done on how natural ecosystems and other campus land use types can act as carbon sinks. This study aims to fill that gap by investigating the carbon stock within Universiti Malaysia Sarawak (UNIMAS) as a study area, using Geographic Information Systems (GIS) tools and Sentinel-2A satellite imagery to quantify Land Use and Land Cover (LULC), including both natural ecosystems and built-up areas. The research focuses on three objectives: to determine the types of LULC in UNIMAS, to quantify the carbon stock in ecosystems such as forests, wetlands, and grasslands, and to determine the CO_2 sequestration potential of these ecosystems. Carbon stock was measured using non-destructive allometric equations, which were then applied to data processed in GIS tools. The results reveal that UNIMAS includes 193.28 hectares of built-up area, with forests covering 98.64 hectares and sequestering 89,975.14 Mg $CO_{2\text{-eq}}$, making them the most significant contributors among natural ecosystems. Grasslands and shrubs cover 36.38 hectares, sequestering 1,467.33 Mg $CO_{2\text{-eq}}$, and wetlands span 14.87 hectares, storing 4,601.74 Mg CO_2 equivalent. These findings highlight the importance of integrating natural ecosystems and LULC management into university sustainability strategies.

1. Introduction

Climate change is a pressing global challenge, driven by the increasing greenhouse gas (GHG) emissions from human activities such as deforestation, urbanisation, and industrial processes (Bajoria et al., 2024). The rising concentration of carbon dioxide (CO_2) in the atmosphere disrupts climate patterns and triggers severe ecological and socio-economic consequences. Natural ecosystems, forests, wetlands, and grasslands play a crucial role in mitigating these emissions through carbon sequestration, absorbing significant amounts of CO_2 and serving as vital resources for both biodiversity preservation and climate regulation. Universities worldwide have increasingly recognised their potential to lead sustainability efforts through research and education and by managing their natural resources. Institutions like Universiti Malaysia Sarawak (UNIMAS) can serve as living laboratories for sustainability, integrating green campus initiatives with advanced research in environmental science. Effective energy management practices have been shown to significantly reduce the carbon footprint (Ochoa et. al, 2022). The green spaces support carbon sequestration and serve as models for other institutions aiming to enhance sustainability through carbon mitigation strategies. For instance, the University of Michigan employed Geographic Information System (GIS) technologies to estimate carbon storage on its landholdings and develop management plans that optimise carbon sinks. Such methodologies highlight the potential for universities like UNIMAS to apply similar approaches to assess their ecosystems' contribution to carbon management. This study focuses on estimating the carbon stock within UNIMAS, leveraging Sentinel 2A satellite imagery and Geographic Information Systems (GIS) tools . While remote sensing offers a scalable and cost-effective means to classify land cover and estimate biomass, it often lacks validation against ground-truth data, raising concerns about the accuracy of its outputs, especially in heterogeneous tropical landscapes. On the other hand, field-based methods, though more accurate, are time-consuming, labour-intensive, and sometimes

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rely on destructive sampling techniques that may harm sensitive ecosystems. This study addresses these limitations by integrating high-resolution Sentinel-2A satellite imagery with non-destructive, ground-based allometric equations to estimate aboveground biomass (AGB). By combining these complementary approaches, this research enhances the reliability and replicability of carbon stock assessments in campus ecosystems, offering a balanced solution that is both methodologically rigorous and resource-efficient. This integrative approach distinguishes the present study from prior works and contributes a novel framework for carbon accounting in higher education institutions. By employing these advanced remote sensing technologies, the research will comprehensively analyse land cover types, focusing on campus vegetation areas. The specific objectives of the study are:

1.To determine the carbon stock and CO_2 sequestration potential present in various land cover types, including forests, wetlands and grasslands;

2.To apply GIS remote sensing techniques for precise land cover classification to support carbon stock estimation in UNIMAS.

This research assesses the carbon sequestration potential of university campuses, such as UNIMAS, to emphasise the ecological advantages of preserving natural ecosystems. It aims to serve as a model for institutions seeking to advance their sustainability initiatives.

2. Method

To establish the basis for this research, the following section first introduces the geographical and ecological characteristics of the selected study area.

2.1 Study Area

Universiti Malaysia Sarawak (UNIMAS) sits in humid, rain-soaked Kota Samarahan, Sarawak (≈1,090 km²; 3,300–4,600 mm rain yr^{-1}). The campus's mix of secondary forest, wetlands and grasslands made it ideal for assessing carbon storage. From Nov 2023–Feb 2024, eight 10 m² vegetation plots per ecosystem were laid out using aerial imagery; all trees ≥ 10 cm DBH were measured and identified to verify supervised LULC maps. Built-up areas were ground-checked by students and staff familiar with the daily landscape.

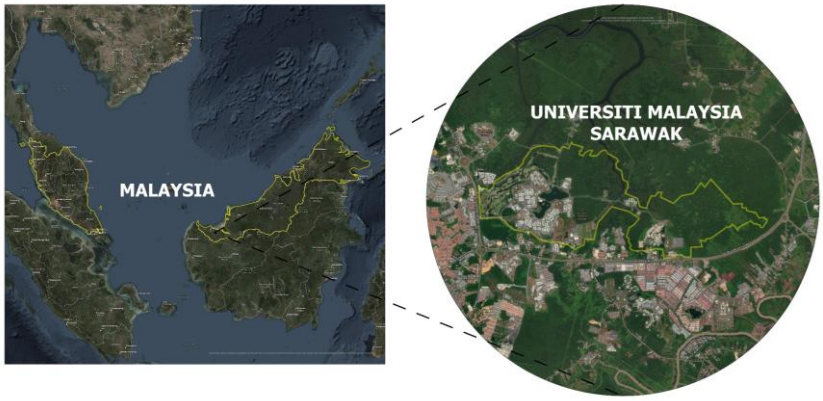

Figure 1: Location of study

2.2 Landholding Data

The study data were gathered through field observations, literature review, and Sentinel-2A satellite images covering the study area. This time frame was selected for its effectiveness in distinguishing forestland from other land cover types. Images were chosen for their accessibility, high spatial resolution, and general quality, with a preference for those having minimal cloud or scene cover. To obtain LULC feature coordinates, Google Earth collected geographic coordinates for point data based on field surveys. 100 sample points were randomly selected to test the accuracy of classified images and validate the LULC classification. Sentinel-2A satellite images from the European Space Agency (ESA) were obtained for the study period, chosen for their low cloud cover and favourable seasonal conditions to enhance land cover accuracy. These images, cloud-free and resampled to a 10 m x 10 m spatial resolution, were processed using ArcGIS for Desktop to classify land cover such as buildings, water bodies, grasslands, wetlands, and forested regions. For land use and land cover (LULC) identification, band combinations, GPS data, Google Earth, and visual interpretation methods were applied. Sentinel-2A was explicitly selected due to its high spatial resolution, which is suited for detailed LULC classification, with bands ranging from 10 m to 60 m. The 10 m bands, particularly in the visible and near-infrared

(VNIR) spectrum (Bands 2, 3, 4, and 8), were utilised to map and quantify vegetation, built-up areas, and other surface features, covering areas with wetlands, forests, grasslands, water bodies, and buildings. In contrast, bands with lower spatial resolution, such as Band 1 (coastal aerosol), Band 9 (water vapour), and the SWIR and thermal bands (Bands 10, 11, and 12), which have a resolution of 20 m to 60 m, are more suited for atmospheric monitoring or thermal observations and will not be utilised in this study. These bands are less relevant for detailed LULC classification, as they capture larger areas and atmospheric conditions rather than surface features. This study aims to accurately map and analyse the selected land cover types by focusing on higher-resolution bands. This study utilised Blue, Green, Red, NIR, and SWIR 1 and 2 bands, as these are commonly employed in vegetation and plant growth analysis. After image pre-processing, a supervised classification technique based on maximum likelihood algorithms was applied, where each pixel was assigned to the class with the highest probability. The resulting LULC maps were used to calculate the area of each land cover category in hectares, providing quantitative insights into the spatial distribution of ecosystems across the study area. This approach of using ArcGIS and Sentinel-2A imagery for spatial analysis has also been successfully applied in similar GIS-based urban land cover studies (She, 2024).

2.3 Carbon Stock from Aboveground Biomass Estimation

Carbon storage and sequestration for each land cover type identified in the LULC maps were estimated using values from two key studies on aboveground biomass (see Table 1). For wetlands, Etigale (2021) was used because it developed allometric equations specifically for *Nypa fruticans*-dominated mangrove forests, which represent about 90 % of the wetlands in the study area. This made the model highly suitable for estimating wetland carbon stock.

For forest areas, the method by Yusoff et al. (2021) was applied, as it focused on secondary forests in a campus setting similar to UNIMAS. Carbon stock estimates were calculated by scaling the carbon density of each land cover type to its corresponding area from GIS analysis. Allometric equations linking tree diameter at breast height (DBH) to biomass were used to determine aboveground biomass (AGB) in sample plots (Figure 4), which were then extrapolated across the landscape.

No specific allometric equation for root biomass in grasslands was found for environments like UNIMAS, likely because grass biomass is usually measured directly through destructive sampling. However, for grass/shrub areas, values from a study by Oo et al. (2006) on multi-species grass and shrub communities were used as a reference.

Table 1: Allometric equation applied for the data

Study	Allometric Equation	Application
(Etigale, 2021)	lnB = -2.373+1.834lnD	Nipa palm in Mangrove Forests
Yusoff et al. (2021)	ln(B) = 2.59×ln(D) - 2.75	Estimation carbon stock in forest campus
Oo et al. (2006)		11 Mg ha^{-1} of carbon stock or 5.35 C Mg ha^{-1} CO_2 sequestration

3. Results and Discussions

The results are organised sequentially, starting with a quantitative appraisal of classification performance as a foundation for later thematic analyses.

3.1 Classification Accuracy Assessment

To assess LULC maps classification accuracy, an error matrix with 50 ground control points gathered through field surveys was used in GIS analysis. Two principal parameters, Producer Accuracy and User Accuracy, have been evaluated, giving a comprehensive assessment of the quality of classification in terms of omission errors and commission errors. Producer Accuracy measures the percentage of true reference samples for a class that were correctly classified. It is a measure of the ability of the classifier to discriminate a class, and is linked to omission error (the proportion of actual features that get omitted or misclassified). For example, the producer accuracy for forests here was 92.60 %, meaning 92.60 % of forested points were accurately classified on the map. User Accuracy, meanwhile, is the percentage of classified pixels for a class that are correct relative to the ground truth. It is related to commission error (features are erroneously associated with a class). In contrast, wetlands had a producer accuracy of 100 % but was predicted on 80.00% of reference data, possibly indicating that all true wetland were detected, but some false wetland points on the reference data did not occur in the field. Kappa coefficient was 0.8992 means indicates good agreement beyond chance and a good robustness of classification.

Table 2: Accuracy assessment for classified study area

Class name	Reference total	Classified totals	Number of corrects	Producer Accuracy	User Accuracy
Built-up area	48	44	43	97.72 %	89.58 %
Forests	25	27	25	92.60 %	100 %
Shrublands/grasslands	7	9	7	77.78 %	100 %
Wetlands	10	8	8	100 %	80.00 %
Water bodies	10	12	10	83.33 %	100 %
Total	100	100	93		
Overall accuracy	93.00 %				
Overall kappa	0.8992				

3.2 Landcover in study area

The result obtained is shown in Figure 4 and Table 3. The supervised classification of the June 2024 LULC map identified various land cover classes, with built-up areas emerging as the most significant LULC type within UNIMAS, covering a land surface area of 193.28 hectares. As a result, it accounted for 53.17 % of the total land area of UNIMAS. For the natural ecosystem land cover types, forests show the highest land cover at 98.64 ha (27.14 %), then grasslands at 36.38 ha (10.01 %), water bodies at 20.31 ha (5.59 %), and wetlands at 14.87 ha (4.09 %). By comparing the built-up area with the natural ecosystem, the built-up area is dominant in UNIMAS, as the total natural ecosystem only covers 46.83 %. However, as vegetation is only considered to sequester carbon through aboveground biomass, waterbodies covered are being ignored. Thus, the total area has the potential to sequester carbon 41.24 % (149.90 ha).

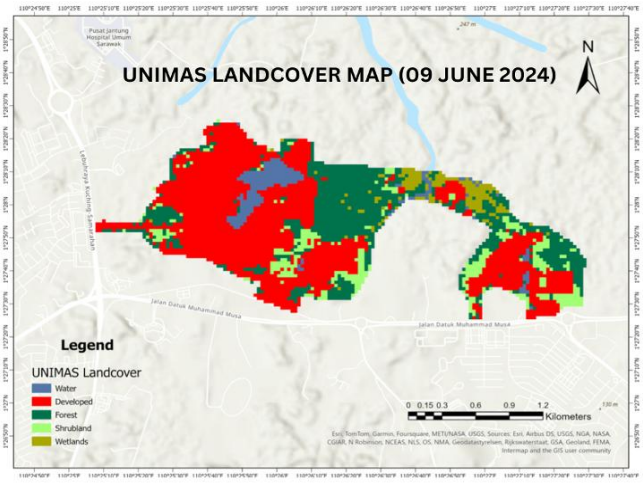

Figure 2: UNIMAS landcover map

Table 3: Land cover typer per area

Land Cover	Area, ha	Total area covered, %
Built-up area	193.28	53.17
Forests	98.64	27.14
Shrublands/grasslands	36.38	10.01
Wetlands	14.87	4.09
Water bodies	20.31	5.59
Total	363.48	100

3.3 Carbon stock from aboveground biomass estimation

A total of 2 sampling plots were inventoried from forest and wetlands areas (refer to Figure 5-6). As the forest land type is more predominant than the wetlands, 20 m x 20 m of the sampling plot will be located in the forest, and the wetlands area is 10 m x10 m. The estimated carbon stock per hectare is taken from the reference studies for the grass. The total carbon stock and carbon sequestration potential are shown in Table 4.

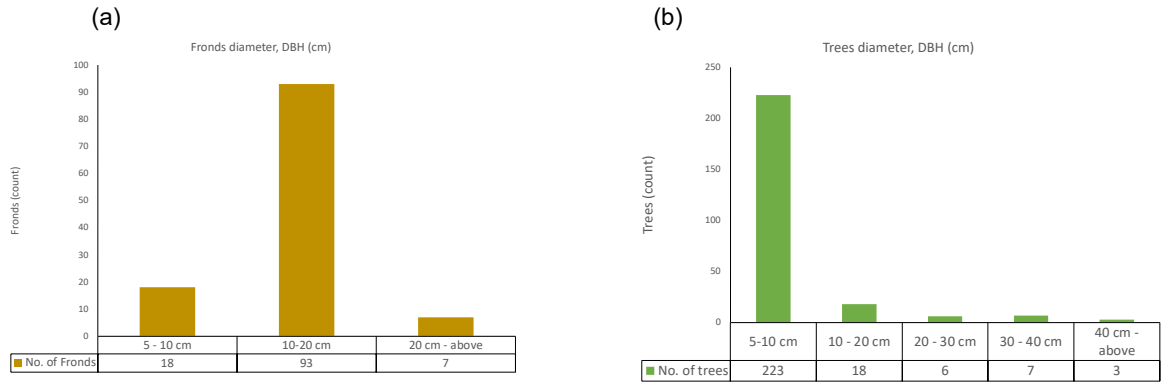

Figure 3: Distribution of fronds diameter at breast height (DBH) in (a) wetlands ; (b) forests

Table 4: Total carbon stock and carbon sequestration based on land cover type

Land Cover	Area, ha	Total, ha	Total carbon stored, Mg	Total carbon sequestration, Mg $CO_{2\ -eq}$
Forests	98.64	497.54	24 538.67	89 975.14
Shrublands/grasslands	36.38	-	400.18	1467.33
Wetlands	14.87	168.80	1255.02	4601.74

The use of supervised LULC classification in ArcGIS, coupled with maximum likelihood algorithms, proved to be the most accurate and efficient approach for differentiating land cover types, especially secondary forests, wetlands, and grasslands. This GIS-based method offers a cost-effective and non-destructive alternative for estimating carbon storage across diverse ecosystems, making it accessible to other universities with similar environmental features. It avoids environmental disturbance from destructive sampling and provides a practical substitute for intensive field surveys of biomass and soil carbon.

For UNIMAS, this methodology offers a strong framework to estimate carbon stock, establish carbon footprint baselines, and guide sustainability initiatives at both campus and institutional level. The use of supervised classification yielded precise results, especially in distinguishing complex tropical land covers such as wetlands and forests. Tropical wetlands act as significant carbon sinks due to their unique sequestration capacity, but accurate classification is essential. Wetland forests may be misidentified as 'forests' and open wetlands as 'grasslands', leading to underestimations of carbon potential. To mitigate this, expert allocation and high-resolution imagery are recommended to better represent sensitive habitats.

Remote sensing challenges, such as mixed pixels and sensor limitations, contribute to misclassification in heterogeneous landscapes. This supports the adoption of advanced classification techniques, especially in complex ecosystems like rainforests or mangroves (Abid et al., 2021). Region-specific classification accuracy is vital to support both carbon estimates and ecosystem monitoring.

In contrast, unsupervised LULC classification, though faster and less demanding computationally, showed significantly lower accuracy. Shadowed areas were often misclassified as water or other incorrect land covers, reducing interpretive value. This aligns with common limitations of unsupervised methods—where computer-generated classes are spectrally homogeneous but may not match meaningful land categories, and analyst control is limited. Given that the land cover classes at UNIMAS are known, supervised classification is more suitable. While it requires greater effort, it allows analysts to define categories, reassess errors, and refine the outputs.

In this study, the time taken for supervised classification varied based on land cover diversity and extent. Areas under 100 ha dominated by a single cover type (e.g., grassland or wetlands) took 1–2 hours for the full workflow: training data preparation, classification, raster-to-polygon transformation, area calculation, and final summarisation. In larger or ecologically complex areas, the process was longer, particularly during raster conversion and polygon processing.

While many universities conduct carbon footprint studies few consider the role of carbon sinks or biosequestration. This study's integration of forest, wetland, and grassland carbon stock data presents a more holistic approach to campus carbon accounting and serves as a model for integrating nature-based solutions into higher education sustainability strategies.

Importantly, ecosystem services provided by green areas, such as carbon sequestration, biodiversity support, and educational opportunities should be formally included in university land-use planning. The Low Carbon Campus Framework 2030 at UNIMAS recognises this contributions, aiming to enhance biosequestration across campus lands. This initiative aligns with global movements by institutions such as the University of Michigan (Tonietto et al., 2021), Bangkok-based universities (Anantsuksomsri et al., 2024), and New Zealand universities (De Villiers et al., 2014) to establish campus-level carbon sinks. However, localised data remains critical for accuracy. Tropical ecosystems like those at UNIMAS differ from temperate forests in carbon dynamics due to climate and species variation, necessitating regional carbon coefficients. Three key insights emerged from this analysis to guide carbon sequestration through campus land management. First, conserving existing natural ecosystems like secondary forests and wetlands provides a low-cost, high-impact carbon offset strategy. While preservation incurs few direct costs, careful planning is essential to maximise ecological value. Second, targeted restoration in high-sequestration areas, particularly wetlands, offers strong potential for carbon enhancement. Third, sustainability policies must consider both ecological and social equity dimensions. Biosequestration should promote access to green spaces and shared stewardship, as urbanisation around UNIMAS increases emissions and alters microclimates.

4. Conclusion

This research reveals the possibility of using satellite imagery with GIS-based supervised classification and allometric modelling for upscaling ABG carbon stock estimation. The research has demonstrated the ecosystem service functions associated with biosequestration and the campus's low-carbon development objectives. The utilization of allometric equations that are validated locally and high-resolution remote sensing have produced trustworthy estimates of areas distribution on land covers and its potential on carbon storage. Nevertheless, this pilot stage had several limitations. The study is a time series snapshot, and seasonal variations in biomass, and vegetation cover were not included, these factors might affect carbon estimation owing to their seasonal changes. Notwithstanding these limitations, the results offer insights for institutional land management and policy making. At the university level, the findings may be used to inform the construction of sustainability scripts, providing guidance to decisionmakers concerning land use zoning. The approach described herein provides a replicable and cost-effective process that other universities or research institutions interested in evaluating and managing their ecosystem-based carbon assets could follow. This study presents a cost-effective, replicable method for assessing campus carbon stocks and underscores the role of campus ecosystems in climate action.

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