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Comparative Assessment of Forest Management System Impact on Carbon Stocks for the Tropical Rainforests in Peninsular Malaysia

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The most recent Malaysian greenhouse gas (GHG) emission assessment has reported that the Land Use, Land-Use Change, and Forestry (LULUCF) sector is crucial as a significant net sink. This feature aids in sequestering substantial CO_2 amounts primarily from forest land, highlighting the necessity of forest ecosystems in climate change mitigation. The impact of Malaysian forest management on forest carbon stocks has also been observed in the Malayan Uniform System (MUS) and the Selective Management System (SMS). This study assessed the impact of MUS and SMS forest management practices on carbon stocks in Peninsular Malaysia. The National Forest Inventories (NFIs) data was employed, which have evolved in their methodology and scope since 1969 to aid the MUS to SMS transition. Given that the MUS could improve commercial timber production by increasing the proportion of commercial and poison-girdling non-commercial species, it performed effectively in lowland dipterocarp forests. The MUS also encountered challenges in hill dipterocarp forests and became infeasible after the country converted numerous readily accessible lowland and hill dipterocarp forests into large-scale agricultural plantations in the 1970s. Consequently, the SMS was introduced in 1978 to replace MUS. This system advocated for adopting sustainable forest management practices, such as annual felling coupes, Reduced Impact Logging (RIL), and conservation efforts for diverse forest species, soil, water, wildlife, and the environment. The data analysis also indicated higher carbon stocks after 1978, suggesting that the SMS significantly enhanced carbon sequestration than MUS. These findings underscored the significance of implementing sustainable forest management practices in Malaysia to preserve carbon and promote economic growth.

1. Introduction

The Malaysian Government submits the National Communication, Biennial Update Report, and Biennial Transparency Report to meet its reporting requirements under the United Nations Framework Convention on Climate Change (UNFCCC). These reports contain a comprehensive record of anthropogenic greenhouse gas (GHG) emissions and removals in four sectors: (i) Energy, (ii) Industrial Processes and Product Use, (iii) Agriculture, Forestry, and Other Land Use, (iv) and Waste (KASA, 2020; NRECC, 2022). A net sink or source denotes a sector or ecosystem absorbing more CO_2 than it releases or the opposite effect, respectively. The most recent GHG Inventory also reported that the Malaysian Land Use, Land-Use Change, and Forestry (LULUCF) sector functioned as a net sink, with approximately 214,714.54 Gg CO_2 eq sequestered in 2019 (NRECC, 2022). CO_2 emissions were primarily absorbed by forest land (92.7 %), while the remaining 7.3 % was absorbed by cropland. The LULUCF sector also emitted 40,956.43 Gg CO_2 eq due to land conversion activities. The forest ecosystems in Malaysia are vital in maintaining the national carbon balance. Various measures (conservation, sustainable forest management, and improved land management practices) possess significant

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potential to mitigate climate change impacts. Carbon sequestration can also be enhanced by reducing deforestation and promoting reforestation and afforestation. Meanwhile, forest ecosystems contain several carbon reservoirs, consisting of living biomass (above-ground and below-ground), dead organic matter (DOM) (dead wood and litter), and soil organic carbon. These reservoirs require comprehension and close monitoring of biomass changes to develop effective management and sequestration strategies. Hence, the National Forest Inventory (NFI) data can develop management strategies while assessing standing stock volume, gross annual increment, and harvest amounts (Röhling et al., 2016). This data is the foundation for calculating biomass carbon stocks using tree allometric coefficients.

The forest carbon stock assessment is becoming more crucial due to climate change and strategies required for improving forest management. Numerous studies have quantified these impacts and evaluated the magnitude of carbon fluxes between forest ecosystems and atmosphere using NFI data (Gibbs et al., 2007), field inventory (Gurung et al., 2015) or remote sensing at regional (Achard et al., 2004) and sub-national levels (Mbaabu et al., 2014). Forest management practices across various forest classifications and types have also been primarily investigated, which are helpful for countries to develop strategies and actions for GHG emission mitigation. In contrast, insufficient forest management system impact on forest carbon stock-related studies have been observed. This inadequacy is likely due to the extended system duration and the need for comprehensive, long-term forest inventory data. The general Malaysian tropical rainforest management has been examined using two forest management system types since 1948: the Malayan Uniform System (MUS) and the Selective Management System (SMS). Therefore, understanding the tropical forest ecosystem reactions to natural and anthropogenic environmental changes is crucial. This process requires systematically quantifying carbon stock changes in forest inventory data over an extended period under MUS and SMS.

2. Evolution of Forest Inventories and Management in Peninsular Malaysia

Malaysia's forest monitoring and management started since 1905. The NFIs have significantly improved forest management and use of forest resources. The First National Forest Inventory (1st NFI, 1969–1972) in Peninsular Malaysia was conducted under a United Nations Development Programme (UNDP) initiative. The Forestry Department of Peninsular Malaysia (FDPM) was also assisted by the Food and Agriculture Organization (FAO). This FDPM then conducted the Second National Forest Inventory (2nd NFI, 1980–1982), which updated forest resource information from the 1st NFI and established new sampling units to maintain the system consistency (JPSM, 1987). The Third National Forest Inventory (3rd NFI, 1991–1992) was performed based on the groundwork laid by the 1st and 2nd NFIs. This inventory was developed through a collaborative effort involving the UNDP, FAO, and the Malaysian Government. Although the system was synchronised with the Continuous Forest Resource Monitoring System (CONFORMS) (JPSM, 1993), this system presented differences from the 1st and 2nd NFIs. Finally, the fourth National Forest Inventory (4th NFI, 2002–2004) and Fifth National Forest Inventory (5th NFI, 2010–2013) were established (JPSM, 2015, 2007).

Forest management in Peninsular Malaysia was influenced by the global timber demand due to shortages caused by the post-war period and the necessity for effective management of industrial timber resources during the early 1940s. The MUS was established in 1948 to transform virgin tropical lowland rainforests into economically viable forests with evenly distributed age groups to increase the proportion of profitable species (Wyatt-Smith, 1963). Conversely, the Malaysian Government implemented extensive agricultural development programmes to address rural poverty during the 1970s, such as the Federal Land Development Authority (FELDA) and the Federal Land Consolidation and Rehabilitation Authority (FELCRA). This introduction led to the transformation of many easily accessible lowland and hill dipterocarp forests into agricultural plantations. Despite the MUS effectively managing lowland dipterocarp forests, the system became less relevant to hill dipterocarp forests. This outcome was attributed to the unevenly distributed trees, insufficient natural regeneration, and uncertain seedling regrowth from potential mother trees.

The SMS was implemented in 1978 as a direct response, highlighting the significance of maintaining forest diversity. This system ensures sufficient growing stocks are maintained post-logging to ensure adequate future timber production, soil and water conservation, wildlife and environment protection, and increased timber species in the wood industry (Chiew Thang, 1987). This study employed the inventory data from the 1st to 5th NFIs to assess the forest carbon stocks under the MUS and SMS forest management practices in Peninsular Malaysia. The inventory data from the 3rd NFI was omitted due to substantial variations in its design compared to prior inventories, resulting in analysis inconsistencies.

3. Materials and Methods

3.1 Site Description

Peninsular Malaysia is one of the significant regions in Malaysia, boasting an extensive area of tropical rainforest (56.9 thousand km^2, 42.95 %) of the total land area (132.6 thousand km^2). The tropical rainforest in Peninsular Malaysia is mainly composed of inland, peat swamp, and mangrove forests. The inland forests consist of four types: lowland dipterocarp, hill dipterocarp, upper hill dipterocarp, and montane forests. These forests are distinguished by their complex structure and numerous plant and animal species. Meanwhile, mangrove and peat swamp forests are usually observed along coastal areas and inland swampy regions. The forests of Peninsular Malaysia are systematically categorised into three main groups to ensure effective conservation, as well as the management of forest ecosystem. Permanent Reserved Forests (PRFs), Totally Protected Areas (TPAs), and Stateland Forests. The PRFs are designated forest areas intended to be conserved and sustainably managed. The TPAs prioritise biodiversity preservation, such as Wildlife Sanctuaries and National and State Parks. The Stateland Forests are designated forest areas set aside for future development. In 2020, the total areas covered by PRFs (48.1 thousand km^2), TPAs (5.1 thousand km^2), and Stateland Forests (3.8 thousand km^2 were calculated (NRECC, 2023).

3.2 Forest Inventory Design

The Malaysian NFI integrates bottom-up and top-down approaches to collect comprehensive forest-related data and information at ground and spatial levels. This bottom-up approach involves gathering forest data and information directly from the ground level using field surveys, operational statistics, and cadastral databases. On the contrary, the top-down approach employs systematic grids and remote sensing tools to examine forest activities (Blujdea et al., 2015). Foresters have utilised field data and information from aerial surveys to develop a complete national forest map by establishing NFIs. Remote sensing technology in forest inventories on the Peninsular was also traced back to 1971. Aerial photographs with scales ranging from 1:25,000 were initially employed to stratify the mixed tropical forests into 11 broad forest types (excluding mangrove forests). Given the advancement of technology, the 3rd NFI used space-based remote sensing data to observe forest changes. Aerial images were also replaced by Landsat Thematic Mapper (TM) data for performing forest inventories.

The commonly used vegetation indices in forest categorisation systems comprise the Normalised Difference Vegetation Index (NDVI) and the Normalised Difference Bare Soil Index (NDBSI). These approaches involved gathering diverse data from different parts of the electromagnetic spectrum. Forest monitoring in the 4th and 5th NFIs was improved by employing SPOT 5, possessing a spatial resolution of 10 m × 10 m. The Forest Resource Map was also overlaid with satellite images to validate the accuracy of the remote sensing imagery in depicting the surveyed forest area conditions. Meanwhile, a significant correlation is generally observed between the field inventory sampling technique and the forest management system employed during the specific period. Considering that the cluster sampling design effectively evaluated the tree population in forests and collected vital tree characteristic data, this design was utilised in the 1st and 2nd NFIs. The tree characteristics examined include volume, value, growth, and species composition in lowland dipterocarp forests. Conversely, the survey designs involving SMS for the 4th and 5th NFIs were modified to stratified random sampling to address the cluster sampling method shortcomings in hill dipterocarp forests. This stratified random sampling is a method where sampling units are randomly distributed throughout different strata, ensuring the full forest area and type representations in data collection.

3.3 Carbon Stock Measurement

The carbon stock in tree living biomass, DOM, and soil organic matter necessitates accurately examining the forest activity-related forest carbon stock. Given that Malaysia has adopted tier 1 assumptions to calculate the carbon stock of DOM and soil carbon, the carbon stocks of dead wood and litter are assumed to remain in equilibrium. This process demonstrates a zero-carbon stock change within the DOM pools. Similarly, soil carbon stocks are presumed to remain unchanged with current stable forest management practices. The carbon stocks in the living biomass of the forest are determined by considering the above-ground biomass (AGB) and below-ground biomass (BGB). The AGB is obtained using an allometric Eq(1) by Brown et al. (1989). This equation ensured consistency between 1st, 2nd, 4th, and 5th NFIs.

$$Y = exp\,\{-3.1141 + 0.9719\,In\,(D2H)\} \tag{1}$$

where Y is the total above-ground biomass; D is the diameter at breast height (cm); H is the total height in (m); and exp denotes e to the power of. The BGB is also determined by multiplying the AGB by the ratio of BGB to AGB for a vegetation type. This process indicates that the BGB estimation relies on the BGB to AGB ratio. The total carbon stock is estimated by multiplying the total biomass by 0.47, representing the carbon content ratio in living biomass within the tropics.

Multiple studies have quantified carbon stock in tropical rainforests using numerous methods. Kato et al. (1978), pioneered assessing the above-ground carbon stock, Niiyama et al. (2010) evaluated below-ground carbon stock, and Istomo (2006) focused on peat swamp forests. Kato et al. (1978) examined two distinct topographic regions: (i) the Lowland Forests of the Sungai Menyala and Pasoh Forest Reserves and (ii) the Hill Forests within the Bukit Lagong and Semangkok Forest Reserves. Brown et al. (1989) developed improved biomass estimation methods based on the NFI data through point and interval estimates. The study covered managed and unmanaged natural forests, including inland and peat swamps. Chave et al. (2005) improved the allometric equations for the tropical regions. The study asserted that the critical criteria for accurately predicting AGB were trunk diameter, wood-specific gravity, total height, and forest type. Furthermore, old-growth forests or forests with natural regeneration were focused on the study. Istomo (2006) also investigated peat soil in Sumatra, Indonesia, while Niiyama et al. (2010) utilised the exact locations for below-ground carbon assessment.

4. Results

Table 1 compares the total carbon stocks over the inventory periods (1972–2012), in which higher carbon stocks were observed after SMS was implemented in 1978. A lower carbon stock during the 2nd NFI was mainly attributed to a smaller forest area, which decreased from 83 to 67.21 thousand km² between the 1st and 2nd NFIs. Although the forest area slightly declined in 2010, the carbon stock in the 5th NFI was higher (see Table 2). The forest growth per hectare also increased, starting with the 2012 inventory. This outcome was attributed to the SMS deployment and the *El Niño* event (1997–1998) (see Table 3). The growth rate in PRFs post-2010 (4.23 tC/ha/yr) was also higher than pre-2010 (2.92 tC/ha/yr). Conversely, the Protected Areas highlighted lower growth rates as biodiversity protection was prioritised and logging activities were prohibited. The forests across the Bornean states also produced comparable growth rates (Banin et al., 2014). This study suggested that selective logging with a limited number of trees removed created gaps in the forest canopy. The process allowed new tree seedlings to thrive, promoting a dynamic forest growth pattern. For example, carbon stocks increased significantly from the 4th NFI (see Table 4). A significantly lower carbon stock during the 2nd NFI period was also attributed to MUS, in which caps on removals were not implemented. The 9th Malaysian Development Plan (2006–2010) enforced and supervised maximum harvest caps.

Table 1: Comparison summary of carbon stocks in Peninsular Malaysia from various NFIs

NFI	1st NFI	2nd NFI	4th NFI	5th NFI
Total Carbon stocks (mil tC)	400.35	272.23	553.03	564.97

Table 2: Comparison summary of the forested areas in Peninsular Malaysia

Year	1970	1980	2000	2010
Forest Area (thousand km²)	83	67.21	59.15	58.64

*Source: Ministry of Natural Resources and Environmental Sustainability, Malaysia

Table 3: Comparison summary of growth rates pre and post-2010

Forest Category	Pre 2010 (tC/ha/yr)	Post 2010 (tC/ha/yr)
Permanent Reserved Forest	2.92	4.23
Protected Area	2.63	2.07

Table 4: Comparison summary of carbon stocks (tC/ha) in logged forest

Forest Type	1st NFI	2nd NFI	4th NFI	5th NFI
Inland forest	173.33	103.19	106.25	193.06
Peat Swamp forest	87.8	94.83	104.96	234.96

5. Discussion

This study indicated a significant correlation between forest management and carbon stocks in the tropical rainforests of Peninsular Malaysia. Given that the MUS was established to manage forests by increasing the proportion of commercial species, all trees with a diameter at breast height (dbh) of 45 cm or less for all species were removed. Selected natural regeneration of varying species (light-demanding medium and hardwood species) was also promoted. Undesired species were then methodically eliminated using poison to round the trunks of all surviving mature trees and non-commercial species with a dbh of 5 cm or more. A regular sampling method was also employed to assess seedling regeneration and confirm sufficient regeneration on the ground for appropriate silvicultural treatments. Even though artificial regeneration with native species was technically possible, large-scale implementation was impractical due to poor accessibility, high establishment, and maintenance costs. The MUS effectively produced commercial timber in lowland dipterocarp forests but was unsuccessful in hill dipterocarp forests. This outcome was due to high seedling mortality from felling damage on steep slopes and inadequate secondary growth response to drastic canopy openings. The poison-girdling down to 5 cm dbh was also considered too drastic, negatively impacting the forest ecosystem (Chiew Thang, 1987).

The SMS was introduced in 1978 into Malaysian forest management practices to replace MUS, primarily due to inadequate natural regeneration of the hill forests. This system enabled a more adaptable harvesting system aligned with environmental conservation regulations and timber market demands. Poison-girdling of many current non-commercial species was discouraged, conserving the wood and the genetic resources available in the forests. This system also effectively handled the highly variable forest conditions in PRFs by implementing felling cycles determined by forest type and tree species. Forest management variables were then optimised, including economic yield, sustainability, and development costs. The general SMS application involves three forestry activity stages: pre-harvesting, harvesting, and post-harvesting. Pre-harvesting activities include conducting inventories to identify trees suitable for logging, establishing cutting limit prescriptions, and affixing wood tags. Harvesting activities encompass forest management techniques (directional felling, RIL, and forest road development) to mitigate negative impacts (Chan et al., 2023). Post-harvest operations encompass conducting inventories and forest surveys to assess the remaining forest condition and perform essential silvicultural treatments.

The data from NFIs and inventories conducted before and after logging activities were used to calculate the annual felling coupes. These inventories also helped govern the specific forest areas requiring harvesting and set volumes of trees to be extracted annually. This strategy guaranteed the efficient extraction of resources and preserving sufficient tree populations for future logging, safeguarding ecological balance and environmental quality. The SMS framework in Peninsular Malaysia also established specific cutting limits for two distinct species groups: dipterocarps (50–65 cm dbh) and non-dipterocarps (45–55 cm dbh). Furthermore, felling cycles were established between 25 and 30 years, with the maximum allowable harvested volume capped at 85 m^3/ha (Chiew, 2009). Likewise, peat swamp forests were a fragile ecosystem requiring careful harvesting effect consideration on the water regime. If enough water were retained, the plant material would continue to be peat. Otherwise, decay could occur if water loss intensified. These forests presented longer cutting cycles (45–55 years) and higher cutting limits (> 40 cm dbh) due to lower natural regeneration rates. In contrast, mangrove forests applied different management practices involving several cutting intervals, ranging between 20 and 50 years. The process involved deliberately cutting down mature trees while preserving a few mother trees. A 3 m wide riverbank and coastal strip were also maintained to promote adequate regeneration and protect the ecosystem (Kassim, 2006).

6. Conclusion

This study successfully investigated sustainable forest management practices involving SMS and MUS. Forests following SMS, annual felling coupes, and RIL demonstrated a significant increase in carbon stock compared to MUS. The MUS increased commercial species by clear-felling all trees down to 45 cm dbh and poisoning non-commercial species. This outcome highlighted the significance of preserving forest carbon stock and responsibly managing natural resources to promote economic growth and development. Although this study presented the effects of forest management on forest carbon stock, additional studies were necessary to understand the impact of climate events on forest carbon stocks and adapt forest management practices to climate change. Future forest policies should also consider the effects of climate change and adapt forest management principles accordingly.

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