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RESEARCH

High regeneration may not contribute to the forest's carbon storage: a case study in the mangrove forest of Rajang-Belawai-Paloh delta, Sarawak

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Abstract The alarming rate of the mangrove ecosystem loss poses a threat of losing valuable carbon sinks. This study was conducted to (i) determine the growth structure in different vegetation types and (ii) compare the aboveground biomass (AGB) and carbon storage in different vegetation types. The study was conducted at four vegetation types within the Rajang-Belawai-Paloh delta i.e., Matured Bakau-Berus Forest (MBBF), Bakau-Nipah Forest (BNF), Regenerating Forests (Debris pile) [RF-D], and Regenerating Forests (Machinery track) [RF-M]. Inventory plots (20 m × 20 m) are systematically located along the main waterways and smaller rivers/streams. Trees (≥ 5 cm diameter-at-breast height [DBH]), seedlings (< 2-cm stem diameter), and saplings (2–4.9-cm stem diameter) were measured. The trend of total trees per hectare is found to be decreasing across the least disturbed vegetation (MBBF) to the most disturbed vegetation (RF-M). The trends of total seedlings and saplings per hectare are found to be going upwards from the least disturbed vegetation to the most disturbed vegetation. Kruskal-Wallis *H*-test showed that there is a significant difference in the AGB and carbon storage between different vegetation types, $\chi^2(2) = 43.98$, $p = 0.00$ with the highest mean rank AGB and carbon storage in BNF (612.20 t/ha) and lowest in RF-M (287.85 t/ha). It can be concluded that although the most disturbed vegetations have higher regeneration, it may not contribute to the forest's carbon storage The naturally regenerated seedlings may not grow beyond the sapling stage unless sustainable forest management is conducted to ensure survivability and growth.

Keywords Anthropogenetic · Biomass · Carbon · Regeneration · Rehabilitation · Sustainable

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Introduction

The anthropogenetic pressures and environmental change have transformed the mangrove forests into one of the Earth's highly vulnerable ecosystems (Sarker et al., 2019). The increase in land development projects for aquaculture and infrastructure has resulted in major mangrove forest loss (Ngoc et al., 2016). Forest harvesting, pollution (Friess et al., 2019), and oil palm plantation (Romañach et al., 2018) then further contribute to the losses.

Moreover, environmental change gradually changes the mangrove diversity and composition from the most diverse and heterogeneous into homogeneous

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forests (Sarker et al., 2019). The displacement of native species such as *Rhizophora* sp. and *Bruguiera* sp. by non-native and invasive species such as *Acrostichum aureum* and *Acanthus* sp. then further restricted the regrowth of the harvested forests (Romañach et al., 2018). The change has started in 1986 and on an increasing trend since then. The environmental change happens largely due to the increased rates of sea level rise, which is the result of climate change (Ngoc et al., 2016; Sarker et al., 2019).

The combined effects of anthropogenetic pressures and environmental change have led to significant geographical variation and eventually resulted in mangrove deforestation and degradation (Scales & Friess, 2019). These will affect the aboveground biomass and carbon storage of the forests (Sakschewski et al., 2016). The ecosystem services and ecological functions provided by mangrove forests, including the protection of water quality, landscapes for ecotourism, protection of shorelines from erosion or sea level rise, and the local economy will also be affected (Sidik et al., 2018).

The importance and threat of mangrove forest losses aided the delivery of global targets including the United Nations Sustainable Development Goals (SDGs), Aichi Biodiversity Targets, the Bonn Challenge, and the Paris Agreement on Climate Change (Turschwell et al., 2020). In due course, more efforts to conserve and restore the mangrove forests have been initiated on the local and regional levels. The Government of Malaysia through the national mangrove restoration project then has initiated the "Tree Planting Program with Mangroves and Other Suitable Species Along National Coastlines" in 2005 (Siti Fatimah & Caihong, 2017). The project focuses not only on mangroves replanting in tsunami-affected areas but also in other parts of Malaysia. As of 2015, a total of 2, 605 ha areas have been replanted with more than 6.3 million trees under this project. These areas have created a conducive mangrove ecosystem, matching the capacity of a pristine mangrove forest. The planted trees have become mother trees and contribute to natural regeneration.

Despite the high potential of mangrove restoration through replanting to recover the ecosystems, there is still a lack of studies on the potential of naturally regenerated mangrove forest to recover the diversity, composition, and capacity of mangroves as carbon sinks. There is also a lack of studies examining the natural regeneration structure and patterns in the mangrove forests (Azman et al, 2021). Naturally regenerated mangrove forests provide an excellent growth model for pristine forests. Hence, this study was conducted to (i) determine the growth structure in different vegetation types and (ii) compare the aboveground biomass (AGB) and carbon storage in different vegetation types. The study includes the inventory of natural regenerations (seedlings and saplings) and trees in four different vegetation types within the Rajang-Belawai-Paloh delta mangrove forests. It is hypothesized that there is a difference in the trend of growth, determined by the ratio of seedling:sapling:tree between different vegetation types with the most disturbed area having higher natural regeneration than the least disturbed area. It also hypothesized that there is a difference in AGB and carbon storage between different vegetation types with the least disturbed area having higher AGB and carbon storage than the most disturbed area.

Methodology

Study area

The study was conducted at the Rajang-Belawai-Paloh delta (Fig. 1). The delta is fed by the three large river systems of Rajang, Belawai, and Paloh. It stretches from Tanjung Manis township, going downriver on Batang Rajang to the river mouth, turning along the coast northward to Belawai, crossing the Belawai river towards the mouth of Paloh river before going inland for about 17 km before going southwards on a small channel into the upper parts of Belawai river. The mangrove forests make up the majority of the forested regions along these rivers. The area also has a variety of other land uses, such as infrastructure, various types of industry, villages, community farmlands, oil palm plantations, and conservation areas.

The mangrove areas experienced commercial harvesting from the late 1970s to the 1980s and were left to regenerate when the harvesting was halted in the early 1990s. Most of the remaining mangrove areas are made up of disturbed forests, maturing regenerated forests, and newly regenerated forests. The remnant forests are mostly logged over, despite having the appearance of being healthy and reasonably intact