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Assessing the Productivity of the Matang Mangrove Forest Reserve: Review of One of the Best-Managed Mangrove Forests

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Abstract: Mangrove ecosystems are crucial for biodiversity and coastal protection but face threats from climate change and human activities. This review assesses the productivity of the Matang Mangrove Forest Reserve (MMFR) in Malaysia, which is recognised as one of the best-managed mangrove forests, while also addressing challenges such as deforestation and climate change-induced factors. This review explores the concept of productivity in mangrove forests, highlighting their role in carbon sequestration and discussing litterfall measurements as fundamental metrics for assessing primary productivity. An analysis of historical changes in MMFR's biomass and productivity revealed fluctuations influenced by logging, reforestation, and climatic conditions. Trends in MMFR productivity indicate a concerning decline attributed to anthropogenic activities such as aquaculture and industrial projects. A regression analysis conducted on *Rhizophora apiculata* data with age as the predictor and AGB as the response variable indicated a positive trend (slope = 3.61, R-squared = 0.686), suggesting a quantitative increase in AGB with age. Further analysis revealed a significant negative trend in MMFR's overall productivity over years (coefficient = −3.974, $p < 0.05$) with a strong inverse relationship (rho = −0.818, $p < 0.05$), indicating declining AGB trends. Despite these challenges, this review underscores the significance of sustainable management practices, effective conservation efforts, and community engagement in maintaining mangrove ecosystem health and productivity. In conclusion, sharing management lessons from MMFR can contribute to global conservation and sustainable mangrove forest management efforts, fostering resilience in these vital ecosystems.

Keywords: productivity; MMFR; decline; *Rhizophora apiculata*; sustainable management

1. Introduction

Mangrove forests are situated in the coastal areas within tropical and subtropical regions, typically between the latitudes 25° N and 25° S, covering approximately 150,000 km^2 globally and occupying less than 1% of coastal regions [1–3]. These ecosystems are characterised as wetlands with abundant vegetation [4]. These unique habitats support diverse plant species thriving in the intertidal zones of coastal and marine environments, encompassing ferns, palms, shrubs, and trees [5].

Their existence in challenging conditions, including high salinity, tidal fluctuations, extreme temperatures, and oxygen-deprived soils, shapes their unique structures and functions [6,7]. These are recognised as the most productive wetlands in tropical and subtropical regions, providing a multitude [8–11] of products, trade opportunities, and vital services [12,13]. Furthermore, their significance extends to mitigating soil erosion, safeguarding coastlines from natural disasters, supporting fish farming, reducing high levels of global warming worldwide, and contributing to the global carbon cycle by acting as coastal carbon sinks [14–18]. Studies have indicated that mangroves exhibit a significantly greater carbon footprint than non-wetland forests. Specifically, it has been observed that the carbon emissions from one hectare of mangroves are equivalent to the destruction of approximately 3 to 5 hectares of tropical forest [19]. This demonstrates their ability to sequester carbon in comparison to other ecosystems. Simply put, the mangrove ecosystem is widely regarded as one of the most productive ecosystems [20]. Since this review focuses on productivity, it is imperative to discuss the concept of productivity in mangroves.

2. Productivity

According to [21], productivity includes four components: biomass increase per unit time, litter turnover, herbivory, and the dissipation of dissolved organic matter from roots. High productivity demands substantial nutrient and trace element inputs to uphold growth and vital physiological functions [22]. Mangrove forests epitomise highly productive and diverse ecosystems, offering ecological, economic, and social benefits [10,11,13]. Evidenced by higher AGB (aboveground biomass) production, amplified net primary production (NPP), lower biomass decomposition rates, and a pronounced AGB to belowground biomass (BGB) ratio, mangrove ecosystems demonstrate a higher carbon storage capacity. These characteristics give mangroves an essential role in mitigating climate change because they can absorb and store three to five times more carbon than other terrestrial forests, predominantly within the soil [16]. However, the escalating pace of mangrove deforestation, exceeding that of inland terrestrial forests with global average losses estimated between 0.16% and 0.39% annually, poses an alarming threat to carbon emissions [23]. Many factors, including changes in the physical or chemical environment, such as soil pH, O_2 concentration, drainage, soil type, nutrients, tides, temperature, and solar radiation, influence riparian vegetation's productivity. The presence of different vegetation types in the tidal zone also affects the production patterns.

Litterfall measurements serve as a fundamental metric used to assess the primary productivity of mangroves [24], compared to other forest ecosystems [25]. Globally, litter productivity values in mangroves range from 2 to 16 tonnes per hectare per year, peaking at 14 tonnes per hectare per year within 0 to 20 latitude locations and dipping below 2 tons per hectare per year in subtropical regions. This suggests that the impact of litter production on latitudinal changes is more complex than that of plant biomass [26]. The accumulation of AGB and the measurement of litter fall represent the most reliable methods for estimating forest net primary productivity (NPP). In the case of mangroves, the average rate of aboveground NPP is 11.1 tonnes of dry weight (DW) ha^{-1} $year^{-1}$, with a decrease in this rate observed as latitude increases [12]. Mangroves exhibit elevated productivity in terms of AGB [22], substantial soil carbon content [16], and a notable proportion of AGB [27] and demonstrate rapid rates of carbon sequestrations [27–29]. These ecosystems are well suited to intertidal conditions, and their primary production serves as a crucial energy source within aquatic food webs [30]. According to a hypothesis, mangrove primary production is transported through marine action to the surrounding areas of the coasts, leading to malnutrition [31]. According to [1], mangroves rank as the second largest marine ecosystem globally after coral reefs, contributing approximately 5% of net primary productivity and exhibiting high carbon sequestration values.

Field studies have consistently showcased the remarkable attributes of mangrove ecosystems, revealing their high productivity [22,32], and significant soil carbon content [16]. Thriving in intertidal conditions, mangroves play a crucial role as primary producers, contributing significantly to aquatic food webs and serving as vital energy sources [30]. Their existence is pivotal for sustaining tropical and subtropical coastal ecosystems, notably supporting fisheries and acting as essential breeding grounds for diverse fish, prawn species, and food sources [33]. The productivity of mangroves exhibits significant variation across different sites [34]. Beyond factors such as climate, soil conditions, hydrology, and human influences [35,36], the structural composition of mangrove forests can significantly influence their primary productivity. This structural aspect directly impacts the photosynthetic capacity of mangroves [37]. Hence, variations in forest structure play a pivotal role in determining the overall productivity of mangrove ecosystems. In the last two decades, there has been a notable shift in paradigms regarding the factors influencing mangrove forest structure and ecosystem dynamics. Previously, forces such as the frequency and duration of tidal flooding, salinity levels, and sediment characteristics (including nutrient availability and redox conditions) were considered the primary drivers. The outwelling hypothesis proposed that mangrove primary production was transported through tidal action to adjacent nearshore ecosystems, sustaining detrital-based food webs [31]. This paradigm shift reflects a more nuanced understanding of the intricate interactions and multifaceted drivers shaping the dynamics of mangrove ecosystems. Measuring productivity is essential to better understand the characteristics of forest ecosystems. Thus, this study focused on assessing the productivity of MMFR (Matang Mangrove Forest Reserve) in Malaysia.

3. Study Area

The MMFR is located on the northwest coast of Peninsular Malaysia [38], in the state of Perak (4°45′ N, 100°35′ E) [39] (Figure 1). The reserve covers an area of 40,600 ha, with 30% mainland forest and 70% island forest [20,40], extending 51.5 km from Kuala Gula to Bagan Panchor [41]. The climate in the MMFR is characterised by moisture. It is influenced by two monsoon seasons: the southwest monsoon, which occurs from May to September, and the northeast monsoon, which takes place from November to the following March. The region's rainiest months are October and November, while it receives an average monthly rainfall of 200–400 mm [42]. According to Chan [42], the Sepetang River's annual mean water temperature is 29 °C, with pH ranges from 6.8 to 7.2, and its salinity in coastal water is between 15.1 ± 0.1 and 24.5 ± 0.5. The tides in this region are semi-diurnal, meso-tidal, with an elevation of the source and tides being 2.69 m and 2.06 m, respectively [43].

Since 1902, the State Forestry Department of Perak has been responsibly managing the Matang Mangrove Forest Reserve (MMFR), focusing on sustainable timber production [39]. This forest reserve is categorised into four distinct forest management groups: protective, productive, unproductive, and restrictive productive forests. The productive zone comprises 110 blocks/compartments, which feature several mature stands of *Rhizophora*. Specifically, this zone primarily contains forests where *Rhizophora apiculata* and *Rhizophora mucronata* are the dominant species [6]. The protective zones, as the name suggests, are designated for protection (Table 1).

The non-productive zones include various areas such as urban villages, lakes, infrastructure zones, charcoal kilns, and offices as identified by [44]. In contrast, the protective zones comprise a rich diversity of mangrove formations, including:

1. *Avicennia-Sonneratia* tree stands: These stands typically comprise young *Avicennia* trees that colonise new mud flats near river mouths. The dominant species in these stands are *Avicennia alba* Blume and *A. officinalis* L. However, patches of *Sonneratia*

alba can also be found in *A. alba* and *A. officinalis* clumps. These stands are submerged during high tides and cover an area of 3299 hectares.

2. *Rhizophora apiculata* tree stands: Found within the protected zone, these consist of *Rhizophora apiculata* and *Rhizophora mucronata* forms that are not subject to exploitation. While *Rhizophora apiculata* predominates, *Rhizophora mucronata* can also be found along estuaries and riverbanks. This stand covers an area of 1665 hectares.
3. Dryland forest stands: These stands represent a transition to the local forest. They are characterised by a forest floor containing high densities of *Acrostichum aureum* Linnaeus and dry deciduous trees [42]. Dryland forest stands have 30 different tree species [45], including four main mangrove species such as stripe mangrove. These dryland forest stands are submerged by the equinoctial tides and are located at higher elevations inland. The total volume of dryland forests spans 2291 hectares [42].

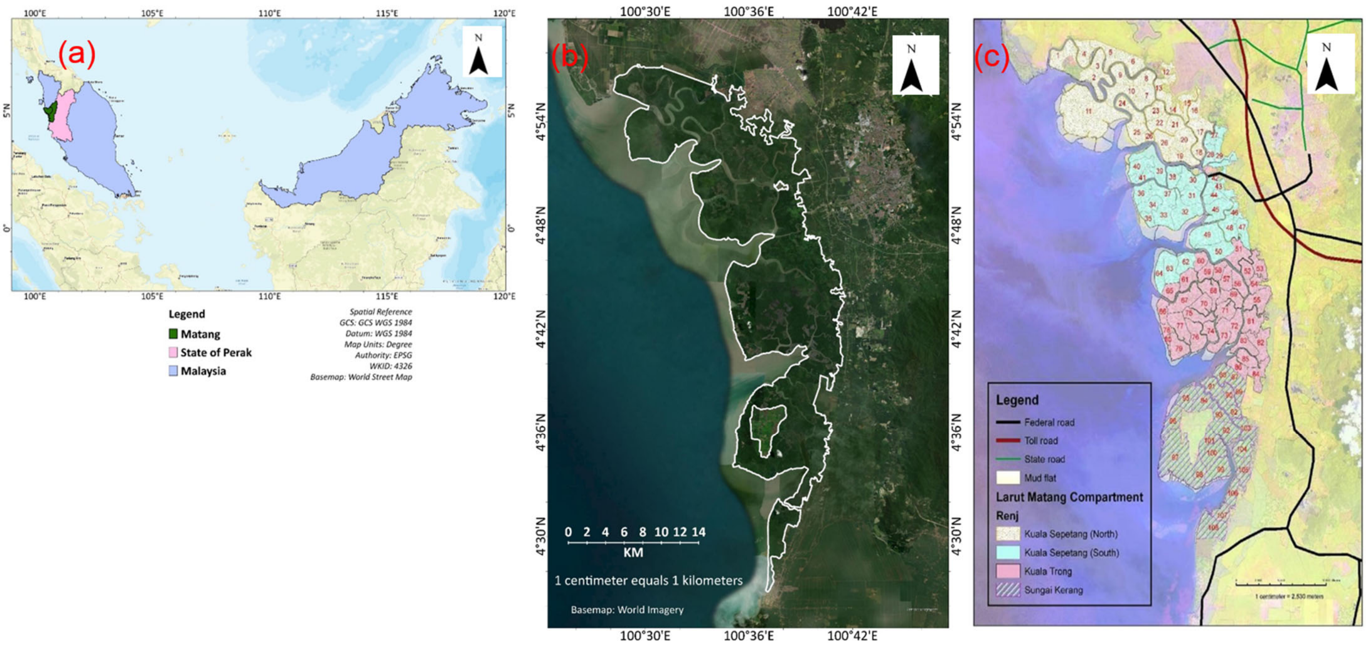

Figure 1. Map of the Mangrove Forest Reserve: (**a**) Location of Matang Mangrove Forest Reserve in Peninsular Malaysia, (**b**) Matang Mangrove Forest Reserve, and (**c**) Compartments in Matang Mangrove Forest Reserve [39].

Table 1. The Matang Mangrove Forest Reserve total acreage breakdown [42].

Range	Compartment	Protective Zone (ha)	Restrictive Zone (ha)	Productive Zone (ha)	Unproductive Zone (ha)	Total (ha)
Kuala Sepetang	1–50 62–64	5164	1369	14,357	179	21,069
Kuala Trong	51–61 65–86	834	480	9560	84	10,958
Sungai Kerang	87–108	1362	1043	5877	157	8439
Total		7360 (18.2%)	2892 (7.2%)	29,794 (73.6%)	420 (1%)	40,466 (100%)

The latest iteration of the Matang Management Plan involves the period from 2010 to 2019, and it adheres to a 30-year rotation system [44]. This comprehensive strategy oversees the management of 110 compartments, facilitating an annual harvest of approximately 1000 hectares of mangrove forests. After logging activities, reforestation involves planting *Rhizophora apiculata* seedlings within one to two years. Management activities entail a two-fold thinning approach: firstly, at the 15-year mark, selectively cutting down smaller trees within a 1.2 m radius; subsequently, after 20 years, conducting a second thinning operation by removing live trees within a 1.8 m radius. The managed forest predominantly comprises single-species stands of *Rhizophora apiculata*, occasionally integrating trees from species such as *Bruguiera parviflora*, *B. gymnorhiza*, *B. cylindrica*, and *R. mucronata* [46]. This thinning process aims to enhance the growth of the remaining trees and procure poles, as highlighted by [47–49].

In parallel, Malaysia has witnessed a troubling decline in mangrove areas, shrinking by 12% from 1980 to 1990 due to various developmental activities, as reported by [50]. Presently, mangrove forests encompass a mere 1.8% of the total land area, with an astonishing loss of over 50% between 1950 and 1985. Notably, the Matang Mangrove Forest Reserve (MMFR), covering over 40,000 hectares and constituting nearly 40% of Malaysia's mangrove area, has experienced a significant decrease in production from 296 tonnes per hectare in the late 19th century to 136 tonnes per hectare in the late 1970s [51].

In response to these challenges, effective enforcement and management strategies are imperative to ensure the conservation and sustainable utilisation of mangrove ecosystems. Given the alarming decline in mangrove areas and productivity, maintaining a consistent monitoring process becomes paramount. Such monitoring endeavours aim to comprehensively assess the structure, plant diversity, and biomass of mangrove forests. Therefore, this study aimed to delve into the productivity of the MMFR over different time frames and scrutinise the factors influencing this decline by analysing previous research findings.

4. Productivity of MMFR

Productivity can be defined as "the amount of biomass produced in an ecosystem". It is denoted in units of kg/m^2/year. Productivity is often linked to the above ground structure of plants [25]. In mangrove-managed forests, i.e., the MMFR, productivity is always defined as the increase in stem diameter and height or tree biomass. Other vegetative and floral parts are ignored in the harvesting process and management. Various studies have been conducted previously to estimate the biomass and productivity of MMFR, and a few studies have claimed that the MMFR is the best-managed mangrove forest in the world [20,49,52]. In the present study, we tried to review all those previous papers and collected the biomass data for different years and different species in the MMFR (Table 2). Table 3 shows the productivity status and trends (indicators) of mangrove forests for different years. The difference table (Table 3) presents an estimated biomass productivity comparison between the current and previous years for two stands of identical age and species. This comparison is denoted by an indicator illustrating whether there was an increase or decrease in productivity.

Table 2. Aboveground biomass of MMRF in different years.

Years	Age	Species	ABG t/ha	Sources
1950	-	*Rhizophora apiculata*	270	[53]
1980	5	*Rhizophora apiculata*	72	[54]
1980	13	*Rhizophora apiculata*	131	[54]
1980	23	*Rhizophora apiculata*	155	[54]
1980	28	*Rhizophora apiculata*	153	[54]
1981	Seedling to mature	*Rhizophora apiculata*	460	[53]
1984	1–10 (5)	*Rhizophora apiculata*	100	[55]
1984	11–20 (10)	*Rhizophora apiculata*	200	[55]
1984	21–30 (15)	*Rhizophora apiculata*	300	[55]
1985	10	*Rhizophora apiculata*	18	[55]
1985	15	*Rhizophora apiculata*	13	[55]
1985	25	*Rhizophora apiculata*	12	[55]
1986	>80	*Rhizophora apiculata*	270	[53]
1986	>80	*Rhizophora apiculata*	460	[53]
1986	>80	*Rhizophora apiculata*	400	[53]
1986	30	*Rhizophora apiculata*	150	[53]
1986 (1950–1981)	Seedling to mature	*Rhizophora apiculata*	409 averages	[53]

Table 2. *Cont.*

Years	Age	Species	ABG t/ha	Sources
1990	-	*Rhizophora apiculata*	185.30	[51]
1990	1–30	*Rhizophora apiculata*	202.53	[51]
1993	5	*Rhizophora apiculata*	8	[54]
1993	10	*Rhizophora apiculata*	90	[54]
1993	15	*Rhizophora apiculata*	100	[54]
1993	25	*Rhizophora apiculata*	150	[54]
1993	30	*Rhizophora apiculata*	300	[54]
1995	20	*Rhizophora apiculata*	228	[54]
2011	15	*Rhizophora apiculata*	216	[52]
2011	20	*Rhizophora apiculata*	217	[52]
2011	30	*Rhizophora apiculata*	372	[52]
2014	>80	*Rhizophora apiculata* *Rhizophora mucronata* *Bruguiera parviflora* *Avicennia officinalis* *Sonneratia alba* *Excoecaria agallocha* *Bruguiera gymnorrhiza* *Bruguiera cylindrical*	415	[52]
2014	15	*Rhizophora apiculata*	216	[52]
2014	20	*Rhizophora apiculata*	217	[52]
2014	30	*Rhizophora apiculata*	372	[52]
2016 (1980–1989)	-	All species in the area	177	[56]
2016 (1990–1999)	-	All species in the area	175	[56]
2016 (2000–2009)	-	All species in the area	179	[56]
2019	15	*Rhizophora apiculata*	168	[20]
2019	15	*Rhizophora apiculata*	235	[20]
2019	25	*Rhizophora apiculata*	241	[20]
2019	25	*Rhizophora apiculata*	283	[20]
2019	30	*Rhizophora apiculata*	266	[20]
		Through remote sensing base		
1991	All age class species	All species in MMFR	153 t/ha	[57]
2011	All age class species	All species in MMFR	140 t/ha	[57]
2017	90 (protective forest)	All species in MMFR	210 Mg ha^{-1} UAV data	[58]
2017	90 (protective forest)	All species in MMFR	143 Mg ha^{-1} ground inventory data	[58]
2017	15 productive forests	All species in MMFR	217 Mg ha^{-1} UAV data	[58]
2017	15 productive forests	All species in MMFR	238 Mg ha^{-1} ground inventory data	[58]

Table 3. Difference table showing trends of mangrove forest productivity.

Years	Difference between ABG t/ha	Estimated ABG t/ha Difference per/year	Indication Increase/Decrease
1950–1980	270–153	117	Decreased
1980–1981	153–460	307	Increased
1981–1984	460–300	160	Decreased
1984–1986	300–400	100	Increased
1986–1990	400–202	198	Decreased
1990–1993	202–300	98	Increased
1993–1995	300–228	72	Decreased
1995–2011	228–372	144	Increased
2011–2014	372–415	43	Increased
2014–2016	372–177	195	Decreased
2016–2019	177–168	9	Same

The dynamics of mature mangrove forests, particularly exemplified by the MMFR, exhibit intricate changes influenced by multifaceted factors. Extensive study [53] in 1986 revealed a historical timeline of transformations within the MMFR. During the 1930s, a noteworthy surge in the population of selected trees contrasted with a gradual decline in *Rhizophora apiculata* growth from the 1920s to the 1950s. Over this period, the relative number of tree species other than *Rhizophora apiculata* contributing to seed production increased between 1920 and 1981. However, the number of trees with a diameter at breast height (DBH) exceeding 10 cm decreased between 1950 and 1975, followed by an increase between 1975 and 1981. Notably, from 1975 to 1981, mortality rates remained constant and did not significantly impact biomass, which decreased from 270 to 153t/ha, showing a variation of 117 t/ha (Table 3). The rapid biomass declined between 1965 and 1975 was primarily attributed to the death of large-sized trees (40–50 cm DBH). Biomass increased from 153 to 460 t/ha in 1981, with a difference of 307 t/year, owing to the planting of seedlings during the 1980s. Similarly, it decreased from 460 to 300 tons per hectare in 1984 due to the felling of some mature trees. As shown in Table 2, a regression analysis conducted on *Rhizophora apiculata* data with age as the predictor and AGB as the response variable indicated a significant relationship (slope = 3.61, intercept = 112.25, R-squared = 0.686), suggesting a positive trend in AGB increasing with age (Figure 2). This highlights how AGB changes with the increasing age of *Rhizophora apiculata* in the MMFR, providing a quantitative measure for comparisons with mangrove chronosequence studies.

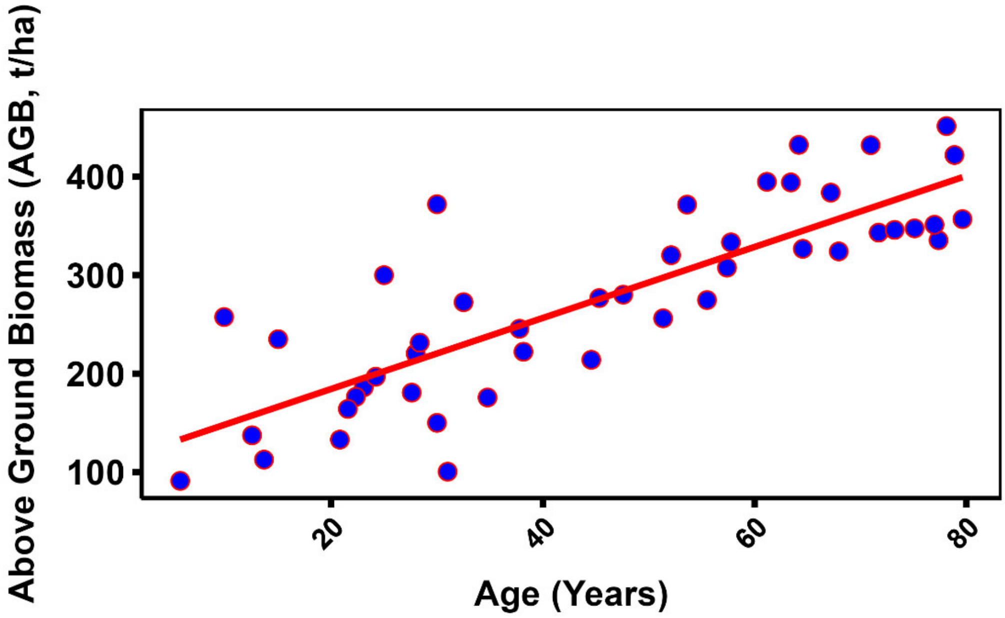

Figure 2. Relationship between age and aboveground biomass (AGB) of *Rhizophora apiculata*.

Old-growth mangroves exhibit high dynamism, notably creating canopy gaps through processes like tree mortality, which are subsequently filled by smaller-statured species, e.g., *Derris uliginosa*. In this ecological theatre, tree saplings on the forest floor emerge as crucial architects of the canopy, actively contributing to its formation. The difference in biomass observed in 1986, approximately 300–400 t/ha (100 t/ha), may be attributed to the felling of some mature trees in 1984, leading to the emergence of root suckers that filled the canopy gaps. In the management of the MMFR, a notable practice involves conducting artificial regeneration two years after the final harvest if the natural regeneration stock falls below 90%. However, the results of these studies should be interpreted cautiously, as many factors influence the dynamics of old-growth mangrove forests. Additional research may be necessary to gain a comprehensive understanding of MMFR productivity. As shown in Table 3, the regression analysis for trends based on years revealed a statistically significant decline in AGB per year (coefficient = −3.974, p = 0.0179), while a Pearson's correlation analysis further supported a strong negative relationship (rho = −0.818, p = 0.0037) (Figure 3). This detailed statistical examination elucidates the overarching negative trend in the MMFR's productivity, offering insight into potential drivers behind these trends and comparing them with historical and current productivity metrics [53].

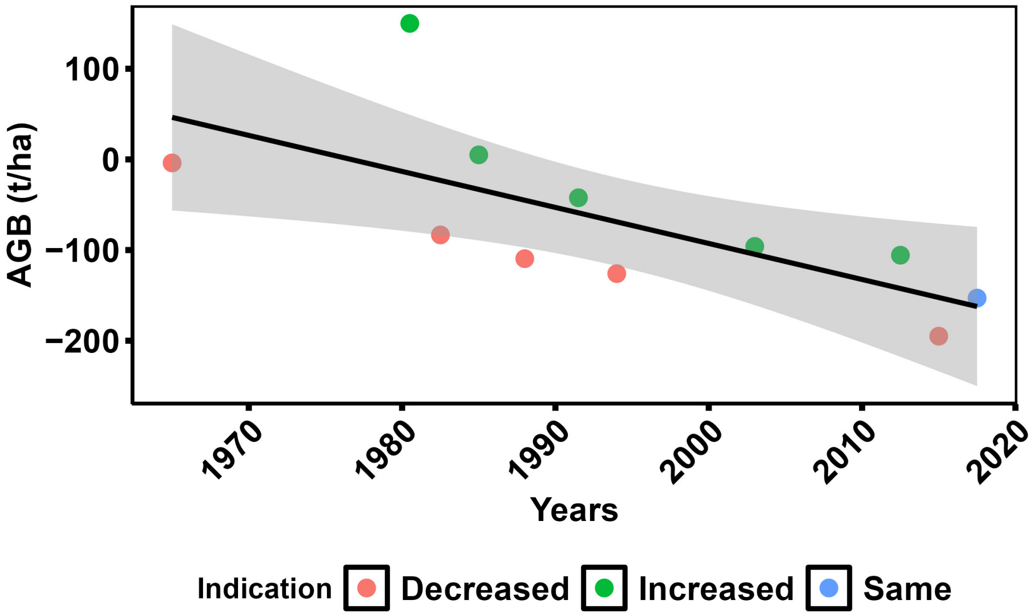

Figure 3. Temporal trends in AGB (t/ha) of mangrove ecosystems over years.

In 1990, there was a significant decline in biomass in the MMFR, with biomass declining from 400 to 202 tonnes/ha over four years, possibly due to logging for wood or charcoal production. Ref. [55] recommended early thinning at 8–9 years of age to increase biomass, followed by first thinning at 12–13 years of age and the next thinning at 17–18 years of age. They also suggested a short rotation of 25 years rather than 30 years because there was no increase in stem biomass after 18 years.

However, biomass increased from 202 to 300 t/ha (98 t/ha difference) in 1993 due to some trees producing good quality seedlings. From 1993 to 1995, biomass decreased from 300 to 228 t/ha, a difference of 72 t/ha, probably due to the presence of numerous mature trees. Ref. [59] supported this trend, highlighting a significant decrease in AGB storage with forest age. Ref. [2] found that net canopy photosynthesis was strongly associated with forest age, although primary productivity decreased with forest age. This surge was attributed to the increase in stand age, progressing from 20 years in 1995 to 30 years in 2011, allowing mature trees to sequester more carbon, thereby contributing to increased biomass. This finding aligns with [51] study, which delineated escalating AGB with stand age progression: 50 t/ha in 5-year-old stands, 70 t/ha in 8-year-old stands, 95 t/ha in 13-year-old stands, and 120 t/ha in 18-year-old stands.

However, in 2014, the difference in biomass was not significant, only 43 t/ha, despite the stand being a mix of different species and older than 80 years. This is because mature trees have a limited capacity to sequester carbon and produce biomass, while younger trees have a greater capacity for growth. Further support for this trend is found in the study conducted by [51], which highlighted rapid biomass increases from 72 t/ha in 13 years to 131 t/ha in 23 years, followed by a decrease from 161 t/ha to 155 t/ha at 23 years. These findings indicate the dynamic nature of biomass accumulation with varying stand ages. In 2016, a notable decline in biomass occurred, reducing significantly from 372 to 177 t/ha and recovering slightly to 195 t/ha. This decline was attributed to the presence of a young stand that year, experiencing amplified seedling mortality, resulting in decreased density and, consequently, lower biomass productivity. Ref. [53] supported this by stating that the death of old trees and their replacement by new trees, which are often more shade tolerant, can reduce biomass productivity. Additionally, ref. [60] highlighted the impact of hot, dry seasons on mangrove ecosystems. Their findings suggested that such climatic conditions could elevate mortality rates and induce long-term declines in living biomass. Consequently, this diminishes the ability of mangrove forests to sustain high net primary productivity (NPP) over time. Environmental factors, e.g., soil abiotic properties, can also affect the productivity of biomass in mangroves [61]. In 2019, biomass productivity did not change significantly, with a negligible difference of 9 t/ha, as the stand age remained the same. This is in line with [62], who observed that the AGB trend of mangrove forests depends on tree age, stand structure, and habitat characteristics.

5. Factors Affecting Productivity

Tropical and subtropical mangroves are valuable for biodiversity conservation and coastal and coral reef protection including seagrass beds [63]. They provide habitat, spawning grounds, and food for three-quarters of commercially hunted species in tropical regions [64]. However, several abiotic factors, such as nutrients, affect the productivity of mangrove wetlands. There is an obvious misconception about mangroves; they are highly productive and rich in carbon but poor in nutrients. Most mangrove research has focused on how mangroves maintain high productivity despite low nutrient availability [65]. Current evidence suggests that mangroves have the capacity for high productivity, even in cases where growth is limited by nutrient availability. This is achievable by efficiently utilising appropriate nutrients and effective nutrient storage mechanisms.

5.1. Nutrients

According to Hutchison et al. [65], mangrove trees are highly productive but poor in nutrients. This is believed to be due to an efficient nutrient cycle and retention mechanism. Mangroves have evolved the ability to store nutrients to survive in oligotrophic, anoxic water and soil conditions. Although the abundances of Na (sodium), K (potassium), S_8 (sulphur), B (boron), and Mg^{2+} (magnesium), N (nitrogen) and P (phosphorus) are likely to be limited in coastal wetlands [30], N and P are considered the most likely limiting nutrients in mangrove ecosystems; these nutrients play a vital role in the robust growth of mangroves. [63,65] discovered that nutrient enrichments such as of N and P perform better in north Queensland. A mixture of N and P encouraged the growth of dwarf mangroves in a coral reef ecosystem off the coast of Belize. Nutrient interactions, soil composition, salinity, and tidal inundation also affect mangrove nutrition [65].

Mangroves have higher nutrient use efficiency for N and a moderate range for P compared to other tropical forests [22]. Mangroves retain N and P by mobilising available solutes and plenty of dead roots. P is fixed with inorganic soil components, for example, Al (aluminium), Fe (iron), Ca (calcium), and S^{2-} (sulphides). At the same time, N is present in the form of $NH_4{}^+$ (ammonium) due to its low energy requirement [22]. Mangrove trees have sclerophyllous leaves and more roots that lead to lower P and water availability than shoot ratios due to water loss through the leaves in highly saline environments. However, high root biomass provides more surface area for nutrient capture and helps to prevent the immobilisation of soil $NH_4{}^+$. Therefore, a non-linear relationship exists between the root-to-shoot ratio and soil condition.

Plants along the riverside are taller and more robust and grow in soils with lower H_2S content than plants detached from the river. This suggests that H_2S concentration is a main factor in controlling the productivity and forest structure of mangroves. The soil ammonification, nitrification, and the conversion of nitrate ($NO_3{}^-$) to ammonium ($NH_4{}^+$) play crucial roles in sustaining primary production within mangrove ecosystems. These mechanisms are pivotal in nutrient cycling, facilitating the availability and utilisation of essential nutrients to support and maintain the productivity of these environments. Any external factor that alters these processes, such as soil disturbance, can negatively affect mangrove productivity [30]. In addition, soil N storage, belowground root production, litter, deforestation, and tidal exchanges can also affect productivity. Ref. [51] conducted a study to investigate the nutrient composition of the MMFR, including N, P, and macronutrient concentrations. The study also examined nutrient export patterns concerning stand age (1 year to 30 years) in productive and non-productive zones. The study found that the concentrations of nutrients in the MMFR follow the decreasing order of Na > Mg > Ca > K (Figure 4).

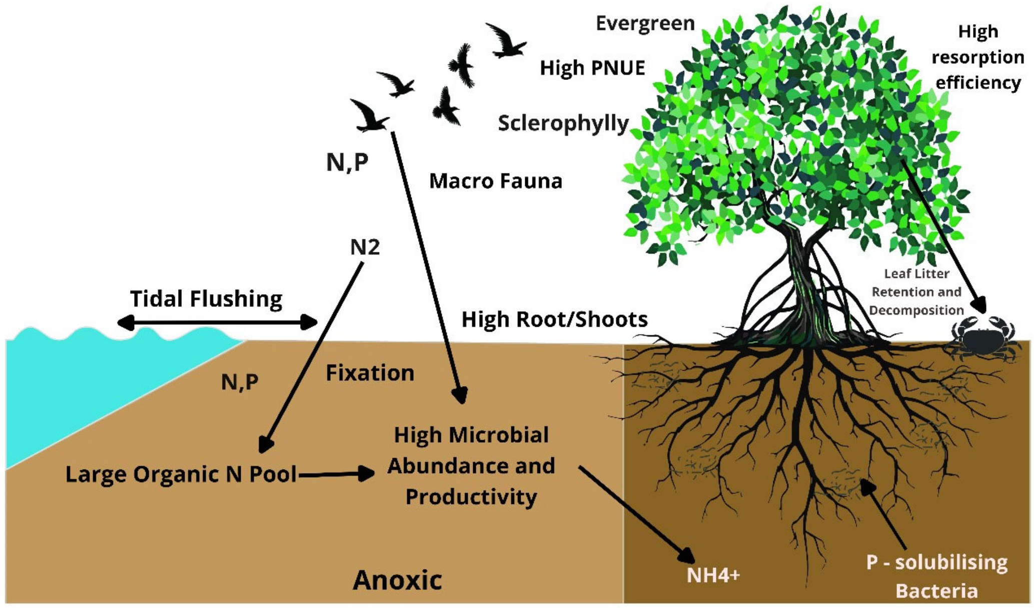

Figure 4. A schematic outlining the primary nutrient sources, which include tidal flushing, nitrogen fixation, microbial activity, leaf litter, and abundant macrofauna, as well as the distinctive nutrient management mechanisms inherent to mangrove ecosystems [66].

5.2. *The Gradient Effect of Flooding*

Several factors cause the absence of understory plantations in mangroves due to stress, for example, insufficient lighting, H_2S (hydrogen sulphide), anoxic soils, soil salinity, and nutrient deficiency nutrients [27]. Snedaker et al. [67] argued that plants cannot meet the energy requirements of the highly stressful environment in the shade of mangroves, so they cannot grow in their shade. Species distribution within mangrove forests is primarily influenced by inundation frequency, pore water salinity, and water logging [27]. Previous research has suggested that the specific substrate elevation is limited by certain characteristics like tide levels, times, and flooding frequencies. Moreover, a recent study by [40], specifically within the MMFR, revealed that flood patterns substantially influence nutrient uptake among similar and different species within the mangrove. This finding underscores the significant impact of flood dynamics on nutrient distribution within these ecosystems.

5.3. *Pollution*

The impact of pollution on mangrove vegetation can be assessed based on biological responses such as biomass composition, defoliation, survival rate, effect on photosynthesis, and the expressions of enzymes. As a weak link between freshwater and marine ecosystems, mangroves assume a vital role in absorbing pollutants and facilitating the flow of nutrients within marine ecosystems. However, increasing pollution pressure from human and natural sources affects these naturally immune ecosystems. Mangroves also act as a sink for heavy metals. They help capture heavy metals such as lead and fluoride by acting as carriers of contaminants [68]. Pollutants and carbon can be trapped in the root tissue, where metal concentrations are generally higher than in the aerial parts. However, mangrove tissues may not be effective pollution indicators because they typically have a lower bioconcentration factor than roots. Metals in mangrove tissues follow the occurrence of metal speciation in sediments. Higher concentrations of Cu (copper) and Pb (Lead) were found to accumulate in root tissue, while Cu and Zn (zinc) were found to be greater than 10% in leaf tissue compared to root [68]. Mangrove sediments, which are generally fine grained, play an essential role in adsorbing chemical pollutants in mangrove ecosystems between pore water, overlying water, and solid phases such as sediments and suspended particles. The precipitation of iron, along with other S^{2-} (sulphide) minerals, e.g., FeS (iron sulphide) in the S^{2-} zones, is responsible for the sequestration of metals in mangroves [67]. A study revealed varying degrees of heavy metal accumulation within the MMFR, with maximum reported levels for manganese (Mn), occasionally accompanied by high levels of iron (Fe), while cadmium (Cd) showed the lowest accumulation. The categorisation generally follows the sequence Mn $\geq$ Fe > Zn > Cr > Pb > Cu > Cd. Several studies were conducted in response to concerns regarding heavy metal contamination in the MMFR. Ref. [69] observed no evidence of heavy metal contamination, while [70] reported low concentrations of heavy metals in the MMFR, possibly attributed to anthropogenic sources.

Development near mangroves has impeded their landward migration. Human activities, such as industrialisation and uncontrolled human activities, have put pressure on untouched mangrove areas. However, mangrove ecosystems can adapt and act as natural pollutant sinks. The MMFR has also been affected by human activities, including aquaculture practices, industrial projects, settlements, charcoal factories, kilns, and piling logs [11].

5.4. Climate Change

Sea level and temperature records are essential for understanding mangrove responses to climate change. Mangroves are anticipated to be among the most vulnerable ecosystems affected by rising sea levels, and their specific response is influenced by the relative mean sea level. The responses of mangroves to climate change are directly affected by anthropogenic drivers such as land-use change, damming, groundwater pumping, exploration for deltaic oil and gas exploration, and aquaculture practices, which affect mangrove sediment budget and influence their rise/fall. The sediment budget and substrate level are influenced by several factors, including surface/groundwater salinity, the hydrodynamics of river basins, sediment volume reaching the coast, the erosion sedimentation balance of the coastline, coastal strip, and the mobilisation of contaminants and nutrients in coastal regions. However, existing sea level and temperature data cannot be used to predict the impact of sea level rise on mangroves [1]. It has been observed that mangroves can withstand sea level rises of up to 9 cm/100 years through peat accumulation, with the rate of peat accumulation in the Hunger Bay mangrove forest being 8.5–10.5 cm/100 years over the last 2000 years based on Holocene records. Changes in sea level, sediment deposition, erosion, soil gap filling, compaction, and microbial decomposition affect mangrove surface elevation [27], and the sedimentation rate determines the response of mangroves to sea level rise. The effects of sea level rise on mangroves depend on location and interactions between the sea level and the watershed, including changes in continental runoff/sea levels caused by different patterns of precipitation [15]. Additionally, the rise in sea level poses an unequal threat to numerous mangrove types and their species. Mangroves growing at the forest's edge, obstructed by natural and man-made barriers, are most vulnerable. Fast-growing species have a better chance of coping with changes than slow-growing species. Climate change is an important factor affecting the distribution and productivity of mangroves [30]. Furthermore, recent investigations highlight the significance of mangrove species diversity in shaping ecosystem resilience to climate change. Studies have shown that diverse mangrove forests with a variety of species exhibit greater resistance and resilience to environmental stressors, including sea level rise, compared to monoculture stands [71]. The functional traits and adaptive capacities of different mangrove species play a critical role in modulating ecosystem responses to changing environmental conditions [72]. Additionally, the provision of ecosystem services by mangrove forests, such as coastal protection, carbon sequestration, and habitat provision, contributes to their adaptive capacity and enhances the resilience of coastal communities to climate change impacts [73].

5.5. Management of Mangrove Forest

The Matang Mangrove Forest Reserve (MMFR) provides a classic case study for sustainable management. It has been a managed forest reserve for the past century. During this time, the reserve lost only 250 hectares of settlements and infrastructure. On the other hand, there has also been an increase in mangrove forests of approximately 1498 ha [48]. In Malaysia, the Forestry Department of Peninsular Malaysia (FDPM) is responsible for policymaking and implementation for mangrove conservation. The FDPM has declared some mangrove forests as reserved to promote sustainable management. This initiative was taken in 1992 by the National Land Council and Forestry Council [74]. For a productive forest like the MMFR, management mostly rests on the supply and demand, and poor management decisions are frequently originated on poor or fragmented pieces of evidence [75]. In some cases, it has also been observed that the mangrove forest has been harvested before the rotation period. There is a possibility that harvesting contractors do not strictly follow the instructions of management when logging operations are taking place. In short, scientific studies can help MMFR management to improve productivity and conservation.

6. Conclusions

The present study critically examined the productivity of the MMFR, offering valuable insights into its management practices as one of the world's best-managed mangrove forests. Through a comprehensive analysis of the existing literature, we assessed the status and trends of its productivity over the years and various factors affecting it. By combining the available research findings, this review highlights the productivity of the MMFR and various factors that could affect its productivity. This study shows an increasing and decreasing trend over the years since 1950. Overall, the productivity of the MMFR has shown a decreasing trend in recent years (Table 3), which could be more possibly due to anthropogenic activities, including aquaculture practices and industrial projects. On the other hand, factors that could contribute to its productivity include sustainable harvesting techniques, conservation efforts, and community engagement. Moreover, effective monitoring systems, adaptive management approaches, and collaborative partnerships can play essential roles in sustaining the productivity and functioning of a particular ecosystem. Furthermore, this analysis emphasises the need to share management lessons from the MMFR to enhance the global conservation and sustainable management of mangrove forests. By drawing on the benefits and challenges found in this exemplary instance, this study aimed to catalyse further research, inform policy formulation, and promote the adoption of best practices in mangrove forest management worldwide.

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