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Historical ecological monitoring and appraisal for extractive uses and other values in Malaysia unveils consequences of regime shifts in 120 years of mangrove management

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A R T I C L E I N F O

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A B S T R A C T

Matang Mangrove Forest Reserve (MMFR) in Peninsular Malaysia, with its 'management plans' traced back to 1904, is the longest-managed mangrove forest for timber (pole/charcoal) production through intermediate thinning and final felling (or clear-felling) operations. For 115 years, the mangroves in the productive zones have been harvested under a 30-year rotation cycle. The 10-year management plans released by the Forestry Department have been supporting silvicultural management. Despite the long management history, the mangrove biomass and quality were found to have decreased in recent years. Therefore, we analyzed all the available management plans between 1904 and 2019 to summarize both qualitative and quantitative data (i.e., silviculture policy/practice and trading) in search of the shifts in management practices. A comparison with relevant literature on the MMFR was also made to evaluate the potential issues of scientific concern in the ongoing management. We found that the higher yield (per ha) of charcoal and poles in the past 20 years resulted from exploiting the restrictive productive zones (=forest that is environmentally sensitive and marginally productive). With a policy inclined greatly toward the financial outcomes of timber-based products, the current silviculture practice may turn out to be unsustainable if any impacts like extreme weather, tree dieoff, sea-level rise, etc., affect mangroves in the future. We discuss the dilemma between greenwood harvesting and the protection of a diverse range of ecosystem service. This study sheds light on the strengths and weaknesses of historic and current mangrove timber harvesting regimes in MMFR and can contribute to supporting future sustainable mangrove management in Matang, and other forest formation.

1. Introduction

Mangroves are plants inhabiting the land-sea interface in tropical, subtropical, and warm temperate areas, most of which are woody trees and shrubs with a few exceptions of palm and herbaceous taxa (e.g., *Nypa*, *Acrostichum* and *Acanthus* spp.) (Dahdouh-Guebas et al., 2021). These plants and their associated organisms constitute the 'mangrove forest community' or 'mangal', whereas mangal and its associated

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abiotic factors make up the 'mangrove ecosystem'(Ibid). Found on sheltered coastlines, the mangroves offer unique goods and services including nursery grounds (Robertson & Duke, 1987), habitats (Nagelkerken et al., 2008), carbon sequestration (Donato et al., 2011), coastal protection (Bennett, 2016), fisheries (Aburto-Oropeza et al., 2008), timber and charcoal (Ariffin & Mustafa, 2013), etc. The socio-economic value of these highly productive ecosystems (Komiyama et al., 2008; MacNae, 1969) implies the need for continuous monitoring and effective conservation/management.

The commercial exploitation of mangrove trees is limited to a few countries in the world (Satyanarayana et al., 2021). Though Indonesia, Thailand, and Vietnam have been producing mangrove charcoal, their documentation records and timber production details are not fully known (e.g. Ilman et al., 2016). Areas like the Sundarbans (Bangladesh) have a long management history (since 1780), but not for commercial felling anytime in the last six to seven decades (Iftekhar & Islam, 2004; Mahmood et al., 2021). Malaysia holds the sixth rank among the nations with the largest mangrove cover (Bunting et al., 2022). Matang Mangrove Forest Reserve (MMFR) in peninsular Malaysia is known as the longest-managed mangrove forest for pole and charcoal production as documented by silviculture records/management plans from 1902 onwards (Ariffin & Mustafa, 2013; Shaharuddin et al., 2005b). The MMFR is divided into productive, restrictive productive, protective, and unproductive zones and managed under three administrative ranges namely, Kuala Sepetang, Kuala Trong, and Sungai Kerang (Ariffin & Mustafa, 2013). Since 1950, mangroves in the productive zone are being harvested for poles and charcoal based on a 30-year rotation cycle (Hamdan et al., 2020). For this purpose, *Rhizophora apiculata* Bl. and *R. mucronata* Lamk. species are chosen due to their high calorific property (UNEP-WCMC, 2006). The first and second thinnings (T I and T II) for mangrove poles are carried out in 15 and 20-year-old-stands, and the final felling for charcoal in 30-year-old-stands (Fig. 1) (Ariffin & Mustafa, 2013; Dixon, 1959). The restrictive productive zone consists of environmentally sensitive and marginally productive forests. While the unproductive zone comprises land-use types without mangroves, the sea-facing mangroves in the protective zone are for land protection (Ariffin & Mustafa, 2013; Muda & Mustafa, 2003).

Despite the existence of MMFR management plans for a long time, no detailed scientific review on historical silviculture was ever done. Though mangroves were found to be sustainably rejuvenating in terms of silviculture, but not necessarily in a context of ecological functionality (Goessens et al., 2014). In fact, issues like declining productivity (Ariffin & Mustafa, 2013), reduced carbon sequestration (Adame et al., 2018; Hamdan et al., 2013), decreased production of bivalves (Abdul Aziz et al., 2015), avifaunal population declines (Sleutel, 2016), etc., were reported in recent years. The amount of quantitative and qualitative data in the management plans can shed light on the solutions for existing problems. An attempt to highlight the history of MMFR management was previously carried out by Shaharuddin et al. (2005) and Muda et al. (2005). However, they only outlined general information about

Fig. 1. Management cycle of Matang Mangrove Forest Reserve (adapted from (Quispe Zuñiga, 2014): (A-B) mangroves restored naturally and/or manually after clear felling; (C) poles harvested from 15-year-old stands through the first thinning; (D) thinning operations using a stick method; (E) poles harvested from 20-year-old stands through the second thinning; (F) Logs harvested at year 30 from the final felling. (G) combustion of greenwood (logs) in the charcoal kiln; (H) charcoal as the final product of burned greenwood. Photo credits: (A-C, E &G-H) Behara Satyanarayana, (D) Management plan 2010–2019 (Ariffin & Mustafa, 2013), (F) Farid Dahdouh-Guebas.

Fig. 2. Map showing the location of Matang Mangrove Forest Reserve on the west coast of Peninsular Malaysia (left panel), with two examples of the forest compartments/coupes (A-B). A) compartment no. 19 as seen from the satellite imagery with the corresponding hand-drawn divisions of the coupes for different pole and charcoal contractors (Quispe-Zuniga, 2014); B) compartment no. 105 as seen from the satellite imagery within the south of the polygon the corresponding hand-drawn divisions of the sub-coupes (Dixon, 1959) (Map source: Google Earth - Landsat/Copernicus 2023).

silviculture rotation, forest types and socioeconomic contribution, without any comprehensive (qualitative and quantitative) metadata analyses to identify the shifts in timber production. Therefore, the present study is unique by focusing exclusively on analyzing MMFR management plans published between 1904 and 2019, together with relevant scientific literature, to identify shifts in the long-standing management regime. The specific objectives were - (1) to extract qualitative and quantitative data (from text, figures, and tables) on mangrove silviculture policy and practice from old/new management plans, (2) to analyze the area, yield, and financial returns of the major mangrove industries (charcoal, firewood, and poles), and (3) to understand the forest management shifts that might lead to conservation and sustainability issues and offer possible solutions. This groundbreaking appraisal can not only support future research and sustainable management of the MMFR but also serve as a valuable reference for mangrove conservation efforts in other regions elsewhere.

2. Material and methods

2.1. Study area

The MMFR is located in the districts of Krian, Larut Matang, and Manjung in the State of Perak on the west coast of Peninsular Malaysia (Lat 04° 15′ –05° 1′ N and Long 100°2′-100°45′ E) (Fig. 2) (Ariffin & Mustafa, 2013). The total area of 40,288 ha (30 % as mainland forest and 70 % as island forest) (Ariffin & Mustafa, 2013) represents 38 % of the mangrove cover in Peninsular Malaysia. There are 34 villages with about 5,300 households or 31,000 inhabitants that live in or close to MMFR (Muda et al., 2005). These communities depend on mangrove forest products, especially through fishing and pole/charcoal production systems, from their ancestral times. Apart from 70 pole and 144 charcoal contractors, there was no official record of the number of workers involved directly or indirectly in the pole/charcoal production yet (Table S1). According to Gan (1995), there were 959 charcoal and 292 pole workers, with another 1,000 indirect employments annually.

Table 1
List of available Matang Mangrove Forest Reserve management plans for the present investigation.

Year	Particulars of the management plan	Availability for the present study
1902	The first action for gazettement by A.M. Burn-Murdoch	No
1904	The first draft of the management plan for island reserves by A.E. Wells	No
1906	Completion of the gazettement	No
1908	The First management plan for mainland reserves by J.P. Mead	No
1915	Management plan revised by J.P. Mead	No
1924	Management plan revised by A.E. Sanger-Davies	No
1925	Management plan revised by J.G. Watson	No
1930–1939	Management plan revised by Durant (1930)	Yes
1940–1949	Management plan revised E.D. Robertson	No
1950–1959	The first 10-year management plan for the first 30-year rotation by Noakes (1952)	Yes
1960–1969	The second 10-year management plan for the first rotation by Dixon (1959)	Yes
1970–1979	The third 10-year management plan for the first rotation by Mahmud (Mahmud, 1969)	Yes
1980–1989	The first 10-year management plan for the second 30-year rotation by Hassan (1981)	Yes
1990–1999	The second 10-year management plan for the second rotation by Gan (1995)	Yes
2000–2009	The third 10-year management plan for the second rotation by Muda and Mustafa (2003)	Yes
2010–2019	The first 10-year management plan for the third 30-year rotation by Ariffin and Mustafa (2013)	Yes
2020–2029	The second 10-year management plan for the third rotation (not released to the public yet)	No

2.2. Mangrove management plans

All available management plans in the libraries of the Forestry Department (Ipoh) and Forest Research Institute (FRIM, Kuala Lumpur) were obtained and photographed/scanned (Table 1). The images were then converted into searchable PDFs and prepared into individual management plan documents. The historical management of the MMFR for timber production started with a gazettement in 1902 and its enactment in 1904. After a series of revisions between 1915 and 1949, the 30-year forest rotation was implemented in 1950. The State Forestry Department of Perak releases management plans for the MMFR every 10 years. Currently, the second 10-year (2020–2029) management of the 3rd 30-year rotation cycle is in place (Table 1).

In addition to the management plans, relevant scientific literature was collected from Web of Science, Google Scholar, and ResearchGate (using 'mangrove', 'Matang', and 'Malaysia' as keywords). Furthermore, the Malay journals like *The Malaysian Forester*, *International Journal of Business and Society*, and *Journal of Tropical Forest Science* (JTFS) were searched. Official websites of the Forestry Department of Peninsular Malaysia (https://www.forestry.gov.my/en/) and the Forest Research Institute Malaysia (https://www.frim.gov.my/) were visited for mangrove governance and related publications. The website of "Connected Papers" (https://www.connectedpapers.com/) (Eitan et al., 2021), which was designed for bibliometric analysis and information visualization, was also visited regularly for scientific articles.

2.3. Data compilation and analyses

2.3.1. General approach

First, a qualitative assessment was done by making a summary of the mangrove management practices including forest type, zoning, silviculture, exploitation and economic evaluation, mentioned in each plan (cf. Table 1). Second, the quantitative information based on the text data and numbers given in Tables and Figures was marked. All the data were extracted manually and incorporated into the Excel worksheets to produce graphs (e.g., trend lines on areas exploited and financial returns of the charcoal industry) and comparison tables.

2.3.2. Area statistics

With the area estimates of different forest zones in the MMFR management plans, the data of both expected (allocated) and determined (licensed) areas of thinning or final felling were used to make trend line graphs.

2.3.3. Yield analysis

Before 1990, the management plans used the local mass unit, pikul, to measure the yield of products. Since 1990, the plan has switched to kilogram (kg) and tonne. In this study, all are uniformly referred to as Megagram (Mg), and pikul was converted to Mg using the equation:

$$Yield(\mathrm{Mg}) = Yield(\mathrm{pikul})*0.0605 \tag{1}$$

The mangrove pole and charcoal yield estimates are available in the management plans. However, for the plans in which these details were not available (e.g. 1980s-2000s for charcoal and 1960–1965 for poles), it was calculated using the following equations:

$$Average\ yield\,(\mathrm{Mg/ha}) = Yield\,(\mathrm{Mg})/Area\,(\mathrm{ha}) \tag{2}$$

$$Determined\ charcoal\ yield(\mathrm{Mg}) = \mathrm{Greenwood} - \mathrm{charcoal\ conversion\ rate} * Determined\ greenwood\ yield(\mathrm{Mg}) \tag{3}$$

$$Pole\ yield\,(\mathrm{Pieces}) = Average\ yield\,(\mathrm{Pieces/ha}) * Pole\ area\,(\mathrm{ha})\ (\mathrm{Since\ 1980}) \tag{4}$$

$$Pole\ yield(\mathrm{Mg}) = Average\ yield(\mathrm{Mg/ha}) * Pole\ area\,(\mathrm{ha})\ (\mathrm{Before\ 1980}) \tag{5}$$

The allocated area was used for expected yield calculation, while the licensed area was used for determined yield calculation. When plotting time-yield graphs, for the period that lacks the accurate number of years, the average yield in ha of the given decade (or five years) was considered.

2.4. Economic valuation

Malaysian currency changed several times in history due to colonization by Britain (as the "Straits Dollar" between 1898 and 1939, "Malayan Dollar" between 1939 and 1953, "Malaya and British Borneo dollar" between 1953 and 1969, "Malaysian Dollar" between 1967 and 1975, and finally "Malaysian Ringgit (MYR)" since 1975 to present) (Bank Negara Malaysia, 2011; Ding, 1966). Therefore, we have taken all possible measures as given below for standardization.

First, the unit prices and total prices (or output value) of charcoal, firewood and poles were obtained from the management plans. In the absent cases (e.g., the 1980s-2010s for charcoal), the total price was calculated using the unit price of the starting year of each decade (1980, 1990, etc.) through the equation:

$$Total\ price\,(\mathrm{MYR}) = Unit\ price(\mathrm{MYR/piece\ or\ MYR/Mg}) * yield\,(\mathrm{Mg\ or\ piece}) \tag{6}$$

Second, the unit and total prices of the mangrove products of different years were converted into total prices in 2010. For years since 1980, the equivalent output value in British Pound (GBP) was calculated using the equation (with the inflation rate referred to IMF DataMapper, 2021):

$$T_{2010} = T_{\mathrm{n}} \times \prod_{i=n+1}^{2010} (1 + I_i) \tag{7}$$

where, T_{2010} = Total price in 2010, T_n = Total price in year n and I_i = Inflation rate of the year i.

The exchange rate of Malaysian currency to other currencies was referred from Schuler (2004). Between 1906 and 1975, the monetary units were equal although they had different names. For years before 1980, when the inflation rate of Malaysian currency could not be found directly, the output value was converted to GBP (1 MYR = 0.1167 GBP) (Ibid.), and then used the inflation calculator to convert the values equivalent to GBP in 2010 (Bank of England, 2021).

For all periods we used the international dollar or Geary-Khamis dollar (G-K$) to compare the values of different currencies (Schmidt, 2021). Here we chose 2010 as the base year to eliminate the effects of inflation. Currently, the international dollar has the same purchasing power parity (PPP) as that of the US dollar (USD).

Using the PPP conversion factor from local currency unit (LCU) to international dollar refers to The World Bank (2021). The output values and unit prices were then converted into 2010 international dollars using the following equation (for years before 1980, the value was converted from the value in GBP to value in G-K$, and for 1980 and onwards, the value was converted from the value in MYR to value in G-K $):

$$Value\ \mathrm{in\ international\ dollars} = Value\ \mathrm{in\ LCU/Implied\ PPP\ conversion\ rate} \tag{8}$$

2.5. Statistical analyses

The variations in mangrove timber yield between the management plans (since the 1980s) were tested through IBM SPSS v. 26 software. Shapiro-wilk normality tests were run to check the normality of the distribution in the pole production data. Due to inconsistency of the data and lack of replicates in management plans, statistical analyses for other data (e.g. charcoal production, firewood production, values of the products, revenue) was unable to do. One-way ANOVA was performed to compare pole production in different decades. Tukey's HSD Test was done for multiple comparisons.

3. Results

3.1. Management policy

Until the end of the 19th century, little was known about the mangrove forests in the Malay Peninsula, let alone the silvicultural requirements or the growth rate of mangrove species. In 1900, commissioned by the British Government, H. C. Hill who was the conservator of forest from the Indian Forest Service, prepared a report on the forest administration in the Federated Malay States. The actions to establish Permanent Reserve Forests took place in 1901. Matang mangroves consist of island and mainland forests. In 1904, the island mangroves were gazetted as a forest reserve. Meanwhile, the first management plan (or working plan) for the island mangroves was drafted by A.E. Wells for a 20-year rotation of final felling and planting. Later in 1908, J.P. Mead formulated a working plan for the reserve of the mainland mangrove forests. The working plans were revised from time to time considering experience. The rotation cycle was first extended to 25 years (1915), and later to 40 years (1924–1940). It was finally fixed to 30 years in the first comprehensive 10-year management plan (1950–1959) of the first 30 years rotation cycle (Noakes, 1952), which is still ongoing today (Table 1 and Table S1).

The stick method for mangrove thinning was originally introduced in 1924 to produce fishing stakes (Shaharuddin et al., 2005b) and later to produce piling materials for housing and construction as well (Chan et al., 1986). Based on the research conducted by A.E. Sanger-Davies (1924), the age of thinning and the corresponding length of the poles were determined. In the 1930s, the T I and T II were conducted for 10 and 20-year-old stands using a stick of 1.5 and 1.8 m, respectively. The third intermediate thinning (T III) was operated with a 2.1 m stick in 35-year-old stands (by the name "regeneration felling") until 1950. From 1950 to 1979, all three thinnings were conducted in 15–19, 20–24, and ≥ 25-year-old stands (Table S2), with only a change in the stick length of 1.2 m for T I. Since the 1980s, the mangrove poles extraction is confined to T I and T II in 15 and 20-year-old stands (Figure S1). Overall, the management plans provided enriched details over the years, especially in terms of silviculture operations, yield, and economics, to compare and understand their shifts in the historical timber production regime of the MMFR (Table S3).

3.2. Forest area

The total mangrove cover was steady at around 40,000 ha during the 20th century, with a decrease in the unproductive zone (unexploitable areas, inland forests, or fishing villages) (Fig. 3A). The restrictive productive zone was however incorporated into the management plans since 2000. The productive area was stable, with only a meager change before and after the 1980s (Fig. 3B). Also, there was no variation in the allocation of the final felling area (including both charcoal and firewood) between 1950 and 1980, while it fluctuated later up to 10,758 ha (Fig. 3C). The firewood portion decreased from 36 to 10 % and finally vanished after the 1980s.

The protected zone increased with a few additional forest types such as new forest (mainly consisting of *Avicennia* at the river mouth) in the

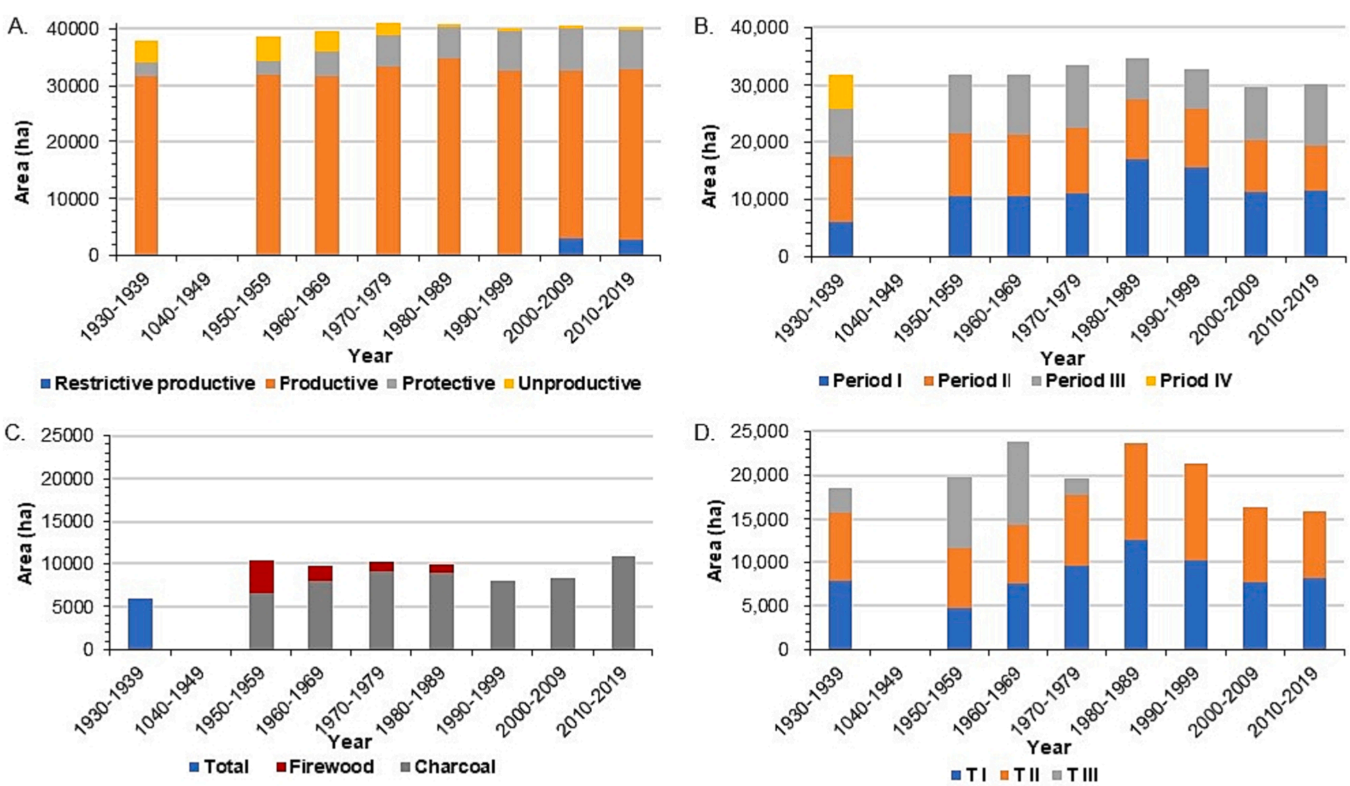

Fig. 3. Matang Mangrove Forest Reserve changes between 1930 and 2010 in Peninsular Malaysia (Ariffin & Mustafa, 2013; Dixon, 1959; Durant, 1930; Gan, 1995; Hassan, 1981; Mahmud, 1969; Noakes, 1952; Shaharuddin et al., 2005a): (A) Total area; (B) Productive area. The productive forest was divided into three periods - Period I, Period II, and Period III consisting of trees of mainly 21–30 years, 11–20 years, and 1–10 years old at the starting year. In the 1930s, a greater extent of mangroves remained virgin, so the forest remaining unexploited on 1st Jan 1930 in the productive area was classified as Period IV (Durant, 1930); (C) Final felling area, and (D) Intermediate thinning area. Missing values in the 1940s were due to the unavailability of the (1940–1949) management plan. (T I = First thinning, T II = Second thinning and T III = Third thinning).

1960s and functional forest in the 1990s (Table S4). Between 1930 and 1979, there were three thinning periods, but the third thinning ceased in the 1980s (Table S2). With a decrease in the T III area between 1950 and 1974, the first two thinning areas gradually increased and reached their peak by 1994 (Fig. 3D and Table S5). The detailed area estimates of each forest zone can be found in Table S4.

3.3. Intermediate thinning

3.3.1. Pole production

Since 1980, the mangrove poles in MMFR were categorized into two types as small (with a diameter of 7.5–10 cm) and big (with a diameter of 10–13 cm), and sold under three standard lengths of 4.9, 5.5, and 6.1 m (Ariffin & Mustafa, 2013). Between 1936 and 1977, the data were inconsistent (along with the impact of World War II in the 1940s) for quantitative analysis (Table 2). The number of pole contractors was maintained between 70 and 75 since 1980 (Table S1).

During the late 1930s, the average yield of poles was 16032.5 Mg annually, while in the 1940s it dropped to merely 11313.5 Mg annually due to World War II. Between 1980 and 2010, pole production from the two thinnings followed a similar trend (Fig. 4A) and showed a significant difference in the total yield of T I and TII (one-way ANOVA, $F(3,36) = [126.848]$, $p < 0.001$). Although it dropped between the 1980s (mean no. of poles: 574,915) and 1990s (502,734), the production in later years (2000–2019: 648,100–975,000 pieces) was significantly high (Tukey's HSD Test, $p < 0.001$). The (mean) number of poles from T I in the 1980s (298,197) and 1990s (275,621) was significantly different from 2000 to 2019 (349,200–611,925 pieces) (Tukey's HSD Test, $p < 0.001$) (Fig. 4B). In the case of T II (Fig. 4C), also pole production in 2010–2019 (345,510) was notably higher than in the 1980s (276,718), 1990s (227,113), and 2000s (298,900) (Tukey's HSD Test, $p = 0.005$).

The poles with a diameter of 7–10 cm have been the major component of T I and T II, while those with 10–13 cm diameter increased by 2010 (Fig. 4B and 4C). Between 1950 and 1965, the yield of poles per ha was in the order of T III > T II > T I. Overall, pole production increased in the subsequent years with a maximum diameter of up to 19.4 cm (Table S6). The production units, expressed in Mg ha^{-1} until 1965, were changed to a number of pieces ha^{-1} in 1980 (Table S6-7).

Missing values for 1930s, 1940s and 1960s are due to inconsistency of management plans and unavailability of the (1940–1949) management plan. The total yield of 1936–1940 and 1942–1949 was documented in the (1950–1959) management plan. The value of 1950–1954 and 1965 was derived from Table S5 and Table S6. The value of 1967–1977 was documented in the (1980–1989) management plan.

3.3.2. Financial returns of pole production

The unit prices of the poles were not available until 1979 in the management plans (Table S8). The total income in the 1990–2000s from the two thinnings was slightly less than in the 1980s, but it almost doubled by 2010 (Fig. 5A). The unit prices of the poles depend on their size (7.5–10 cm or 10–13 cm in diameter) than on their length. The poles with a 10–13 cm diameter contributed majorly to the financial returns of the intermediate thinning (Fig. 5B and 5C). Financial returns (total value) of the pole production varied significantly between T I and T II (one-way ANOVA, $F(3,36) = [26.448]$, $p < 0.001$). The mean value of the poles from T I was prominent for 2010–2019 (2,27,346 G-K $) compared to the 1980s (1,251,761 G-K $), 1990s (1,083,154 G-K $) or 2000 s (1,114,324 G-K $) (Tukey's HSD Test, $p < 0.001$). For T II, there was a significant difference between the 1980s (1,355,856 G-K $) and 1990s (903,999 G-K $) (Tukey's HSD Test, $p < 0.001$), and between the 1990s and 2010s (1,338,459 G-K $) (Tukey's HSD Test, $p < 0.001$).

3.4. Final felling

3.4.1. Yield and financial returns of charcoal

The number of charcoal contractors increased from 27 to 144

Table 2
The yield of poles through first (T I), second (T II) and third (T III) thinnings (Mg) between 1936 and 1977 from Matang Mangrove Forest Reserve in Peninsular Malaysia.

	1936–1940	1942–1949	1950–1954	1955–1959	1960–1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977
T I (Mg)	–	–	16,110	22,538	34,660	2,578	–	6,426	3,881	8,364	2,342	12,469	6,744	8,269	2,812	5,563	6,565	8,261
T II (Mg)	–	–	46,988	23,200	38,245	14,231	–	1,218	6,205	2,802	15,069	8,600	8,215	6,288	3,204	10,219	8,844	4,336
T III (Mg)	–	–	82,133	80,739	106,390	22,812	–	12,756	3,573	2,561	1,377	1,311	546	177	3,021	581	0	0
Total (Mg)	80,163	101,822	145,231	126,478	179,295	39,621	–	20,400	13,659	13,727	18,788	22,379	15,504	14,734	9,037	16,363	15,408	12,597

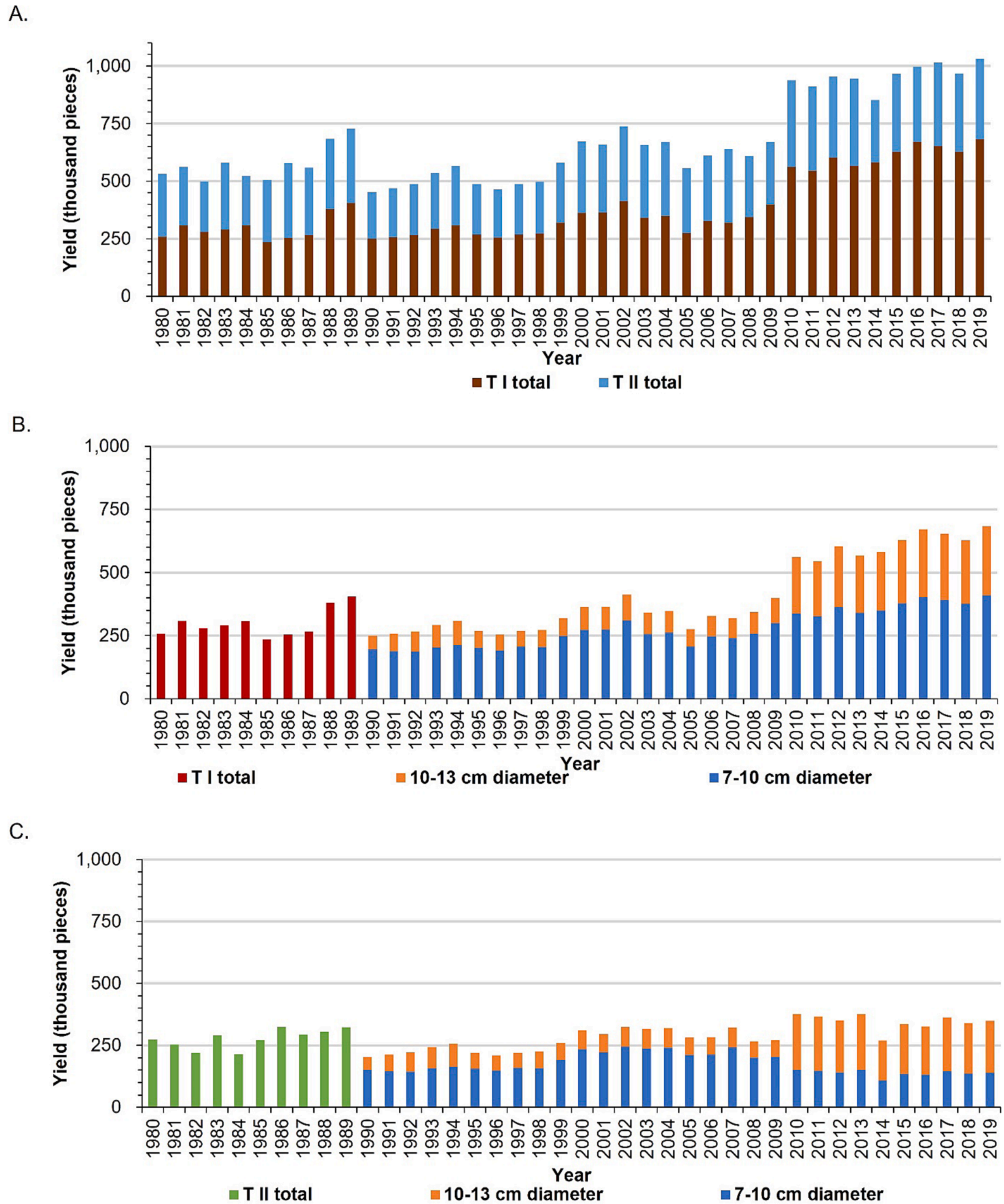

Fig. 4. The yield of poles in total and in detail from Matang Mangrove Forest Reserve in Peninsular Malaysia: (A) Yield of poles from both T I and T II (1980–2019); (B) Yield of poles from T I (1980–2019); (C) Yield of poles from T II (1980–2019). In (B) and (C) the poles were mainly with a diameter of 3.2–9.6 cm. The yield of poles by 1976 was the actual number determined after the management period. The yield since 1980 was estimated using the allocated area and the yield per ha of poles in the starting year (T I = First thinning and T II = Second thinning) (Ariffin & Mustafa, 2013; Gan, 1995; Hassan, 1981; Shaharuddin et al., 2005a).

between 1950 and 2019. However, with the regulation of having max. 3 kilns per contractor, its count was restricted to less than 400 since 1970. The allocation of mangrove area for each kiln also changed periodically, increasing from 1.62 to 2.7 ha in 1950–1979, furthur rising to 2.8 ha in 1980–1989, then decreasing to 2.3 ha in 1990–2009, and finally stabalizing at 2.2 ha in 2010–2019. The rapidly increased production of charcoal during the 1930s was affected by the Japanese occupation and World War II in the following decade (Fig. 6A). Between 1966 and 2002, the total charcoal yield fluctuated while dropping. Concerning the yield of charcoal per ha, it was mostly around 40–50 Mg ha^{-1} (Fig. 6B). After the downtrend between 1950 and 2000s, the yield per ha gained momentum and reached a peak under the management period of

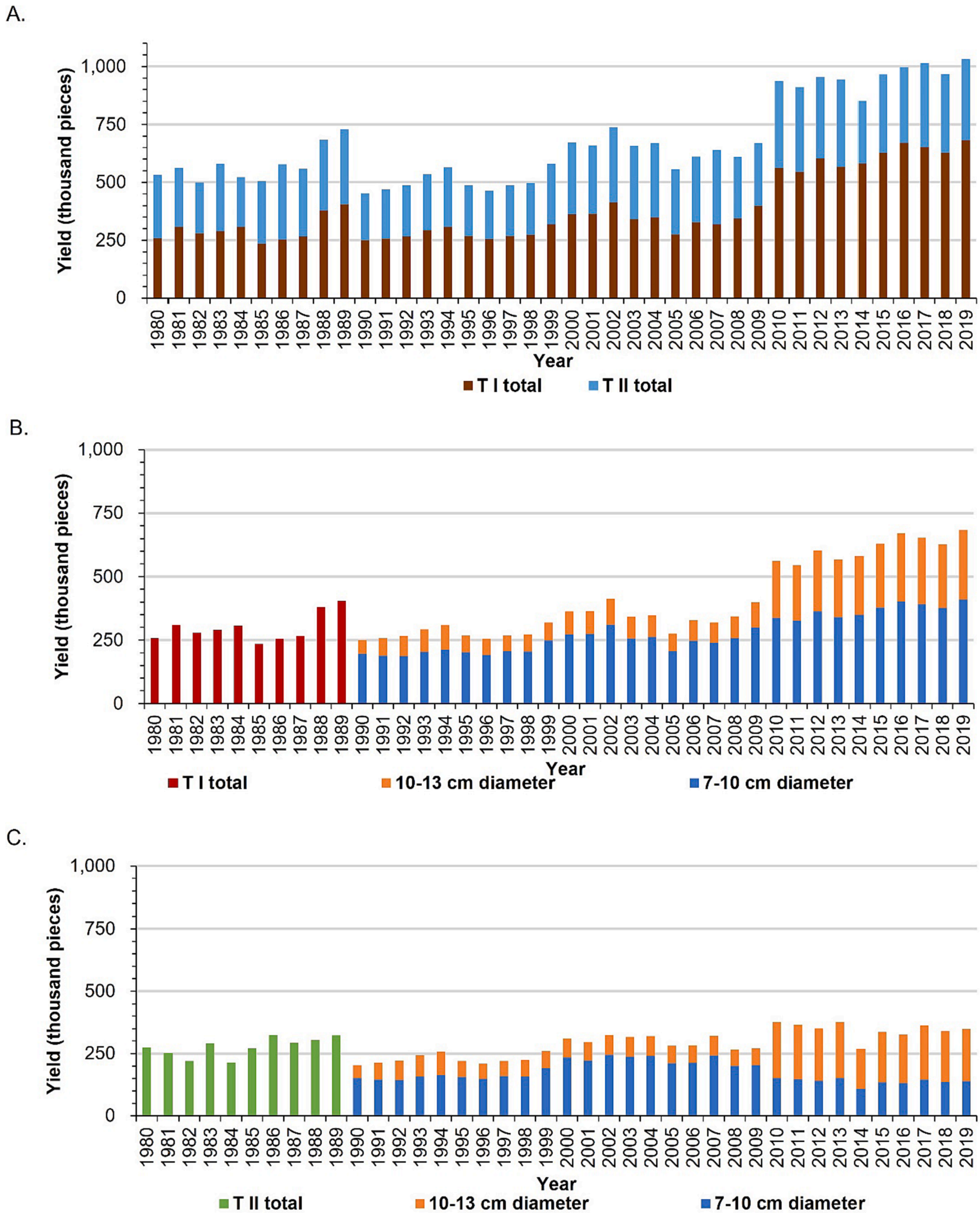

Fig. 5. Financial returns of the intermediate thinning at Matang Mangrove Forest Reserve in Peninsular Malaysia: (A) Total financial returns of the poles (expected). The value of the poles was estimated based on the yield of the previous decade and the price of the starting year; (B) The detailed financial returns of poles from T I (expected); (C) The detailed financial returns of poles from T II (expected) (TI = First thinning and TII = Second thinning) (Ariffin & Mustafa, 2013; Gan, 1995; Hassan, 1981; Shaharuddin et al., 2005a).

2000–2009. The unit price of charcoal grew from the 1930s (except for the 1940s) to the 1980s (Fig. 6C). Although it decreased consistently between 1990 and 2000, the management period of 2000–2009 seemed to be a profitable turn with the peak in 2009. The greenwood-charcoal conversion rate of 0.29 in the 1960s and 1970s was reported to be 0.27 since 1980.

3.4.2. *Mangrove firewood*

Early in 1949, the annual yield of the firewood was declared to be 96,655 Mg. However, it decreased to 53,543 Mg in the 1970s and further

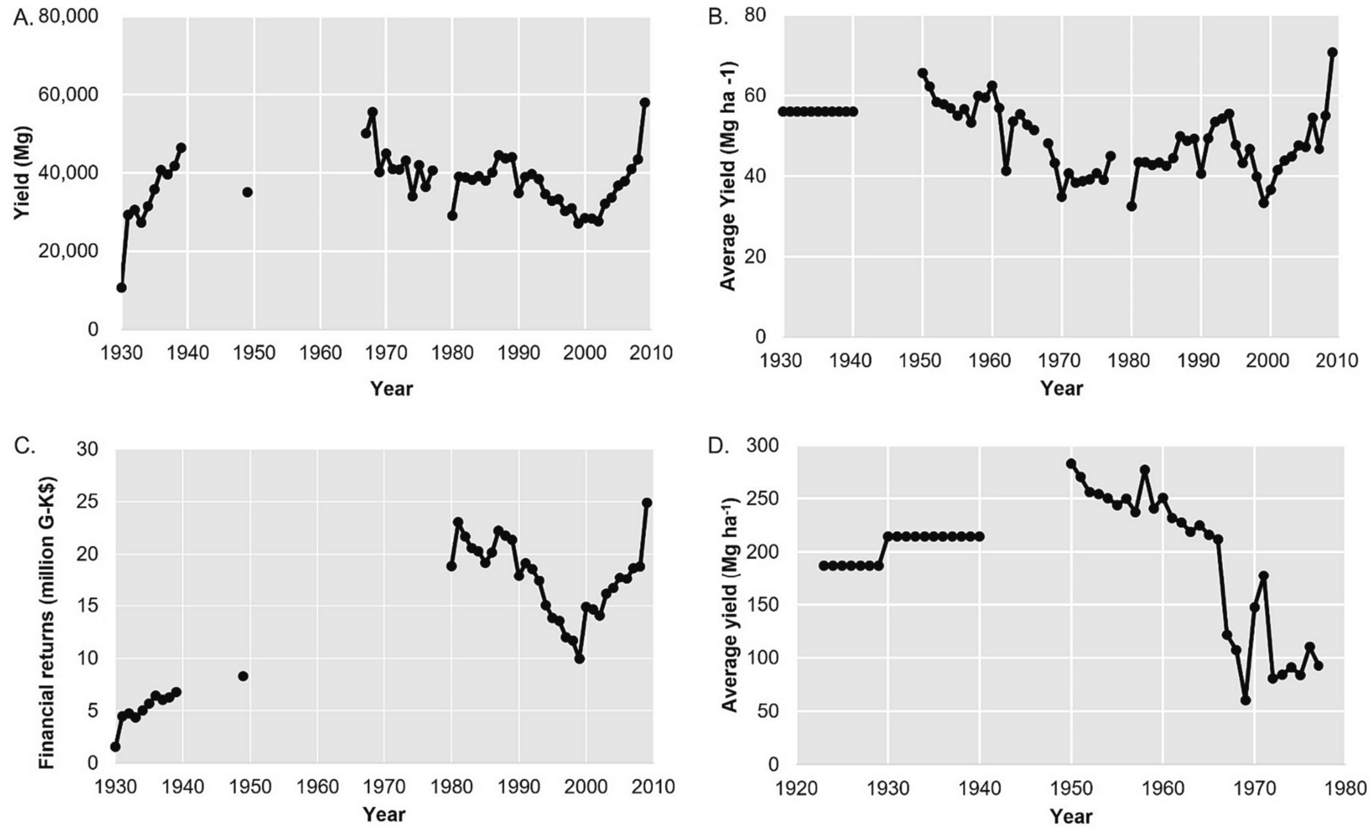

Fig. 6. Yield and value (total price) of final felling products at Matang Mangrove Forest Reserve, Peninsular Malaysia: (A) The yield of charcoal; (B) Yield per ha of charcoal; (C) The financial returns produced by charcoal; (D) The yield per ha (average yield) of firewood. The value (total price) of charcoal and firewood was determined by the actual yield and the price of the starting year. Missing values in panel A-D were due to the unavailability of the management plan (1940–1949) and the inconsistent details (Ariffin & Mustafa, 2013; Dixon, 1959; Durant, 1930; Gan, 1995; Hassan, 1981; Mahmud, 1969; Noakes, 1952; Shaharuddin et al., 2005a).

dropped to 10,000 Mg in the subsequent years. Since 1980, the firewood yield was unspecified, and its industry was terminated in the 1990s. The average firewood yield per ha was high in the 1950s and low in the 1970s (Fig. 6D). The value (total price) of firewood in the 1940 s equals the higher purchasing power of G-K$ 1,767,257. However, by the end of the 1990s, its annual estimated value was reduced to one-third (equivalence of the purchasing power of G-K$ 620,225. The price of firewood did not change significantly with the inflation rate between 1980 and 1989 (170.51 G-K$ Mg^{-1}) and 1990–1999 (155.06 G-K$ Mg^{-1}) (Table S8).

3.4.3. Paybacks to Forestry Department

The annual revenue (royalty and premium) of mangrove timber to the State Forestry Department of Perak reached up to 1,971,957 G-K$ (Table 3 and Table S9). A royalty is a legally binding payment made by an individual or company for the exploitation of greenwood in MMFR as well as its marketing (poles and charcoal). A premium is an installment payment for the insurance policy in MMFR. The revenue that equaled purchasing power in the 1930s (G-K$ 315,331) reached its highest for 1970–1979 (G-K$ 2,298,178), and lowest in the recent decades for 2000–2009 (G-K$ 1,137,141) (Table 3). The expenditure in different decades has resulted in fluctuating net revenue of the MMFR.

4. Discussion

4.1. Mangrove area changes

The global mangrove loss since the 1990s was more than 1.04 million ha (FAO and UNEP, 2020). Instead of the loss slowing its pace down in the late 20th and early 21st century (Friess et al., 2016; Friess et al., 2020; Hamilton & Casey, 2016), the countries like Myanmar, Philippines, Malaysia, and Indonesia are still listed as primary/secondary mangrove deforestation hotspots in Southeast Asia (Gandhi & Jones, 2019). There have been several reports on the loss of mangrove cover in Malaysia. For instance, Chong (2006) identified 111,046 ha (ca. 16 % extent) of mangrove loss across the nation between 1973 and 2000 due to agriculture, aquaculture, urban, and industrial developments. For Peninsular Malaysia, Gopalakrishnan et al. (2021) made a constructive analysis based on historical archives and recent satellite (Landsat) data between 1853 and 2018. They too claimed > 400 km^2 (ca. 31 % of the

Table 3
The financial status of revenue and expenditure in the management of Matang Mangrove Forest Reserve, Peninsular Malaysia (G-K$ = Geary-Khamis dollar).

	1930–1940	1949	1950–1959	1960–1969	1970–1979	1980–1989	1990–1999	2000–2009	2010–2019
Total revenue (G-K$ /annum)	315,331	1,119,356	1,098,744	–	2,298,178	2,254,724	1,936,449	1,137,141	1,971,957
Expenditure (G-K$ /annum)	165,159	215,119	386,949	–	–	446,852	1,149,339	874,724	845,124
Net revenue (G-K$ /annum)	150,172	904,237	711,795	–	–	1,807,873	787,110	262,417	1,126,833

*The values for 1930–1940 and 1949 are actual revenue and expenditure (Noakes, 1952), while the values for the rest of the years were predictions (Ariffin & Mustafa, 2013; Gan, 1995; Hassan, 1981; Mahmud, 1969; Shaharuddin et al., 2005a). Missing values of 1960–1969 and 1970–1979 are due to the inconsistency of management plans.

original extent) of mangrove loss since 1944.

By comparing the clear-felled areas of the MMFR management plans with the L-band synthetic aperture radar (SAR) data (1988–2017), Lucas et al. (2020) found progressive logging of forests as they matured in each coupe of the productive zone. Although they noticed a few differences between the proposed and the operated timings of final felling, the present study confirms that the cumulative felling area remained the same during the 30 years (Figure S2).

In MMFR, Ibharim et al. (2015) indicated a net loss of 5,019 ha between 1993 and 2011 due to coastal erosion, tree harvesting rotation, aquaculture, illegal agricultural activities including oil palm plantation, and trespassing. However, the data obtained from the management plans of the 1990s, 2000s, and 2010s show neither the productive zone nor the total area experienced changes of more than 3,000 ha. As the mangrove loss areas identified by Ibharim et al. (Ibid.) and Abdul Aziz et al. (2015) are mostly confined to landward margins, the local authorities should take further actions to confirm and provide details (including up-to-date maps) in the new management plans. The decline of mangrove forests due to human-induced stress is a common phenomenon (Adeel & Pomeroy, 2002; Dahdouh-Guebas et al., 2004; Hamilton & Casey, 2016), let alone that most mangrove forests are considered under less proper management than MMFR (Goessens et al., 2014).

4.2. History of the poles industry and market

After World War II in the 1940s and limited greenwood exploitation in the 1950s, the mangrove pole industry recovered substantially. The purpose of T III was to induce natural regeneration before final felling was successful (Hassan, 1981; Noakes, 1952), but this happened to stop with the implementation of a 30-year silviculture rotation in 1980. The decrease in the price of poles in G-K dollars during the 1980–2000s was because of the higher inflation rate (Figure S3). Later, the pole market evolved competitive with a saturated number of sellers (Muda & Mustafa, 2003). In the 2010s, the merchantable poles of the MMFR were acknowledged as the best quality poles with high straightness, minimal tapering, and monospecificity that fit for construction purposes, especially for piling (Ariffin & Mustafa, 2013). The increased (average) yield of 10–13 cm diameter poles in the 2010s (besides the same allocated area and the number of contractors as in previous decades) (Table S7) was due to the exploitation of the restrictive productive zone for final felling activities in the 2000s. In light of the durability and pest-resistant characteristics, *Rhizophora* poles have immense demand in Southeast Asia and Africa (Bennett & Reynolds, 1993; Kairo et al., 2002; Riungu et al., 2022; Weinstock, 1994).

4.3. Silvicultural practices

Several researchers have offered suggestions for the thinning operations at the MMFR. For instance, Abdul Aziz et al. (2015) observed early and intensive intermediate thinning and final felling that caused an unstable regeneration rate and fluctuation in greenwood yield. Gong and Ong (1995) and Fontalvo-Herazo et al. (2011) proposed an extra early thinning before T I and T II at the age of 7–9 years to minimize the loss of (exploitable) greenwood out of natural thinning. Also, Goessens et al. (2014) suggested either reducing the stocking density of propagules or increasing the planting space between them to avoid wood loss before 15 years. In fact, Gong and Ong (1995) recommended mangrove plantations if the natural recruitment after two years of final felling is less than 50 % (instead of 90 % at present) which also highlights the need for a new replanting policy. Although Goessens et al. (Ibid.) supported T I and T II at 15 and 20-year-old stands, Gong and Ong (Ibid.) and Fontalvo-Herazo et al. (Ibid.) suggested 12–13 years for T I and 17–20 years for T II. So far there were no attempts to validate these propositions, but it is necessary if the authorities plan to bring any changes to the ongoing management in the future.

4.4. History of the charcoal industry and market

Mangrove charcoal is still preferred for traditional cooking and barbecue in local and overseas markets (Satyanarayana et al., 2021). Compared to firewood of other origins, it has a higher capacity for heat retention and less smoke (Gan, 1995). Early in 1930, when the charcoal kiln was first introduced from Thailand, Durant (1930) predicted that the Malaysian charcoal industry would expand to capture both local and overseas markets. Its expansion was so fast that by 1940, there were as many as 300 kilns in full operation (Idris, 2005). However, the Japanese occupation and World War II affected the implementation of the MMFR management (1940–1949) plan for the 1942–1945 period (Noakes, 1952). In the 1950s, the charcoal industry recovered with demand from overseas like Singapore and Hong Kong (until the 1970s) (Ariffin & Mustafa, 2013). Despite the increased area of charcoal production between 1950 and 1970s (Fig. 3C), its less yield (Fig. 6A-B) was perhaps due to declined biomass/productivity. The reduced yield of greenwood in the second (1960–1969) and third (1970–1979) 10-year period of the first 30-year rotation cycle was also reported by Abdul Aziz et al. (2015). They claim that MMFR is susceptible to periodical declines in the average yield of greenwood extraction.

In the 1980s and early 1990s, the market of charcoal was confined to Perak and neighboring states within Peninsular Malaysia. Even though charcoal imported from Indonesia and Thailand was available for a cheaper price in the local market, the majority of people preferred using MMFR charcoal (Gan, 1995). The reason for having an increased (average) charcoal yield per ha in this period (Fig. 6A-B) could be linked to the areas of final felling with the period I (21–30 years old) vegetation (Fig. 3B). Since the 1990s, MMFR charcoal found its new market in Japan for barbecuing, tea making, and water purifying (Ariffin & Mustafa, 2013). The export of MMFR charcoal to Japan increased from 300 Mg in 1991 to 12,000 Mg in 2000. This was further raised to 30 % of the total production in 2000–2009 (Muda & Mustafa, 2003) and 80 % in 2010–2019 (Ariffin & Mustafa, 2013). The demand for (mangrove) charcoal in the Japanese market clearly explains the growth of its yield in MMFR through increased final felling area and the number of charcoal contractors (Ariffin and Mustafa, Ibid.).

However, in terms of the financial returns, not all stakeholders in the charcoal production system of MMFR are well benefited. According to Satyanarayana et al. (2021), the contractors are the main economic beneficiaries whereas the workers like charcoal bearers, fire monitors and packing persons, are still paid less than the minimum wage. Such financial dissimilarities among the stakeholders were also noticed in the industry of charcoal production from non-mangrove resources (as making mangrove charcoal is illegal) in many countries like Tanzania in Africa (Satyanarayana et al., 2021; The World Bank, 2009). Since one-third of the wood fuel production in pantropics was unsustainable (The Charcoal Project [TCP], 2021a), the charcoal-producing forests should be under targeted management to enhance sustainability (The Charcoal Project [TCP], 2021a, 2021b). For MMFR, the ongoing 30-year rotation period was found to be appropriate from the point of silviculture management and productivity (Fontalvo-Herazo et al., 2011; Goessens et al., 2014).

4.5. Fade out of the firewood industry

Before the 1950s, firewood was the main forest product of MMFR (Gan, 1995), and was even used for the Malayan railway in the early 20th century (Muda et al., 2005). Although its demand surged between 1920 and 1950 due to tin mining and other industrial/domestic usage (Durant, 1930), later declined with the increased use of cleaner fuel resources (oil and electric power) (Gan, 1995). In this context, the limited transportation of bulky firewood products to other markets / adjoining villages is noteworthy (Chan et al., 1986). The allocation of firewood sub-coupes in poor-quality forests with low standing volumes also affected its yield per ha after 1950 (Fig. 6D) (Hassan, 1981). The details of the firewood production were not available in the management plans since 1990 which also coincides with the discontinued allocation of the forest for firewood production.

4.6. Conservation and sustainability concerns and possible solutions

With the early records of forest harvesting before 1900 and more systematically from 1904 (Ariffin and Mustafa, 2013), the MMFR is undoubtedly supporting the longest recorded mangrove management regime for timber production in the world. This historical management was also said to be a reference point for other countries to learn and manage their mangrove resources wisely (Goessens et al., 2014; Marajan, 2005). However, balancing the forest products usage and ecosystem services has been a challenge in many parts of the world, including for MMFR. Given the main objective of MMFR to produce poles and charcoal out of 80 % productive zone, the 30-year silviculture rotation was preferred to achieve maximum timber production in the shortest possible time.

In fact, the forestry department of MMFR conducted both national and international workshops, training (capacity building) courses, and conferences regularly to welcome expert advice for sustainable management. In the recent (2010–2019) management plan, Ariffin and Mustafa (2013) identified several research needs like – the economic viability of timber production, coastal sedimentation, volume tables, lightening strikes, boat wakes and ethnomedicine, of which some studies have already been completed in association with the Forestry Department (Amir, 2012; Drouet Cruz, 2022; Hugé et al., 2022; Satyanarayana et al., 2021; Wolswijk et al., 2022).

In the past 20 years, higher yield (per ha) of charcoal and poles at MMFR was found to be associated with the exploitation of restrictive productive zone (personal communication with Mr. Harry Yong, Forestry Department (Ipoh), 2019). According to Otero et al. (2020), some coupes in the dryland forest where final felling took place belong to the protective forest. The mangrove ecosystem services are largely regulated by age, species richness, and structural complexity (van Oudenhoven et al., 2015). When there is a low species diversity there are also chances for a lower ecological redundancy, functionality, and resilience against the extreme weather events or climate change impacts (Goessens et al., 2014). Given the main objective of the MMFR management for poles and charcoal production, the ongoing practices do have a considerable impact on biodiversity. For instance, Sleutel (2016) found less avifaunal communities (species richness and total taxonomic diversity) in the productive forest stands compared to the protective forest. Also, Martínez-Espinosa et al. (2020) raised similar concerns in relation to the brachyuran crab populations. According to Mohd Khatib (2021), 15 out of 16 estuarine fish populations were represented by a negative allometric growth for which the disturbed or polluted environment (including over-fishing) is responsible. Overall, there is an imperative need for research on the mangrove biodiversity vis-à-vis management of the MMFR.

Recently, protective and restrictive productive zones were found crucial for balancing the carbon stock of MMFR as they neutralize the carbon emissions from the charcoal production and functioning as stable carbon sink (Wolswijk et al., 2022). For instance, if the productive zone (30,120 ha) is also managed like a protective zone then it would not only bring mangroves to a well-recovered state with rich carbon sequestration (as it takes > 70 years to approach the accumulation rate of undisturbed forests), but also raises the worth of the ecosystem services equivalent in purchasing power to G-K$ 34,44 million in ten years (Adame et al., 2018). This is close to the market value produced by the forest products (G-K$ 38.8 million) in 2010–2019 (Ariffin & Mustafa, 2013). However, the chances for such dramatic changes are almost nil, unless the mangroves face severe losses due to extreme weather, tree die-off, sea-level rise, etc., as part of the changing climate. Even in such conditions, there may be a gradual reduction in timber production (phase by phase) rather than an immediate ban due to several mangrove-dependent communities in the vicinity. This also cautions not to increase the area of mangrove exploitation and the number of pole/charcoal contractors.

In light of the growing and competing demand for food, biofuels, and timber on one hand and environmental challenges due to climate change on the other, the idea of decentralization in forest governance was informed (Agrawal et al., 2008). However, its application to mangrove forests like MMFR and a good balance with REDD + need further understanding (cf. Phelps et al., 2010; Ribot et al., 2006). The community-managed forests are usually known for less destruction/deforestation in the tropics (Porter-Bolland et al., 2012). Though some researchers have mentioned MMFR as the best-managed mangrove forest (e.g. Ariffin & Mustafa, 2013; Chong, 2006; Gong & Ong, 1990; Okamura et al., 2010), still there are several ecological and economic uncertainties to attain sustainability. As of now, MMFR management is inclined more toward the economic approach than the ecological approach, and hence, there is a need for additional policy research from ecological aspects by the forestry department to predict and face the challenges of the changing climate in the future and to include all local stakeholders equally (Hugé et al., 2016; Martínez-Espinosa et al., 2020).

5. Conclusion

We combed through the history of charcoal, poles and firewood industry and management in MMFR. During 1942–1945, WWII seriously damaged the ongoing management and monitoring of MMFR, and all three of the timber-based industries were devastated, then gradually recovered after the war. The expansion of the pole/charcoal industry could initially be linked to the decline of firewood production in the 1980s and later to the exploitation of restricted productive zone in the 2010s. Even if the MMFR tends to show periodical changes in its greenwood production, concerns were raised through this study. Improper replanting and intermediate thinning policy that induce wood loss due to self-thinning, thus adjustments to silvicultural policy are required. Since there was mangrove loss due to many reasons, especially at the landward margins, we suggest the forestry department take further actions on efficient and sufficient mangrove monitoring and provide up-to-date maps. There was intensive exploitation of mangroves to meet the huge demand for charcoal and poles, so we suggest the management supported by biodiversity conservation and ecological sustainability factors. As the policy of MMFR inclined greatly towards the financial outcomes of timber-based products, not all stakeholders are well considered in the management policy. There is a great need for future management to include all industry and local stakeholders equally to support their livelihood. Meanwhile, additional research on ecological aspects by the forestry department is required. Addressing these concerns will not only reduce the dilemma between greenwood harvesting and ecosystem service protection values but also help to come-up with necessary changes in the ongoing management policy. Apart from the pole/charcoal production, this study points to the importance of exploring further into the wealth of information on ecotourism, nature education, fishery, aquaculture, etc. that can be explored further.

CRediT authorship contribution statement

Danyang Chen: Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualisation. **Behara Satyanarayana:** Methodology, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Supervision. **Giovanna Wolswijk:** Investigation, Resources, Data Curation, Writing – review & editing, Visualisation, Supervision. **Nur Hannah Abd Rahim:** Writing – review & editing, Visualisation. **Ahmad Aldrie Amir:** Writing – review & editing, Supervision. **Jean Hugé:** Writing – review & editing, Supervision. **Farid Dahdouh-Guebas:** Conceptualisation, Methodology, Validation, Investigation, Resources, Data curation, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jnc.2024.126582.

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