Macintosh *et al. Carbon Footprints* 2023;2:14
DOI: 10.20517/cf.2023.26

Carbon Footprints

Original Article

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Growth and carbon stocks in four mangrove species planted on a former charcoal concession site in Ranong, Thailand

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How to cite this article: Macintosh DJ, Ashton EC. Growth and carbon stocks in four mangrove species planted on a former charcoal concession site in Ranong, Thailand. *Carbon Footprints* 2023;2:14. https://dx.doi.org/10.20517/cf.2023.26

Received: 17 May 2023 **First Decision:** 25 Jun 2023 **Revised:** 3 Jul 2023 **Accepted:** 24 Jul 2023 **Published:** 31 Jul 2023

Academic Editor: Daniel M. Alongi **Copy Editor:** Fangyuan Liu **Production Editor:** Fangyuan Liu

Abstract

The ending of mangrove concessions for charcoal production in 1998 gave new impetus to mangrove conservation and rehabilitation in Thailand, including the designation of the Ranong Biosphere Reserve (RBR) to protect Thailand's largest single mangrove ecosystem. Four of the dominant tree species in the RBR were planted as seedlings in single species blocks on a former concession site in 1994: *Rhizophora apiculata* (Ra) and *R. mucronata* (Rm); and 1995: *Bruguiera cylindrica* (Bc) and *Ceriops tagal* (Ct). Tree growth and natural recruitment of seedlings and saplings were recorded in 100 m^2 sampled quadrats in each species block in 1999, 2008, 2019 and 2023. All four species exceeded 10 m mean height by 2019 (range 12.1 ± 3.8 m to 19.6 ± 2.3 m), while mean DBH was 7.5 ± 3.4 cm to 9.1 ± 6.9 cm. There was evidence of self-thinning mortality by 2023, especially in the Ra and Bc blocks. Some illegal cutting of Bc trees between 2019 and 2023 further impacted the growth performance of this species, which exhibited a compensatory strategy of self-planting many seedlings. The height and DBH of the four planted species in 2023 were still less than in a mature *Rhizophora*- and *Ceriops*-dominated conservation forest area (mean tree height 17.4 ± 6.7 m; DBH 15.1 ± 7.3 cm). However, soil organic carbon (SOC) was high and not significantly different between the monoculture species blocks (525 ± 107 Mg C ha^{-1} to 743 ± 31 Mg C ha^{-1}) and the conservation forest (616 ± 91 Mg C ha^{-1}). SOC accounted for 74%-90% of the total ecosystem C, which was 650 to 829 Mg C ha^{-1} in the planted species blocks and 828 Mg C ha^{-1} in the conservation forest. The estimates for plant, soil and ecosystem C are compared with those reported from other natural and planted mangrove sites in Southeast Asia, especially along the Andaman Sea coast. The findings confirm the importance of conserving the few remaining areas of near-primary mangrove forest in this region.

Keywords: Mangrove, rehabilitation, tree growth, recruitment, carbon, Thailand, Southeast Asia

INTRODUCTION

Mangrove forest ecosystems in Southeast Asia have been exploited heavily over many decades for fuelwood (especially charcoal), pole wood, timber and wood for the paper industry. They continue to be exposed to a wide range of threats, including degradation caused by wood extraction, conversion to other land uses and climate-related impacts, especially sea level rise[1-3]. More recently, however, Southeast Asian countries have given priority to mangrove conservation in order to recover the wide array of mangrove ecosystem functions and services lost or degraded by their unsustainable exploitation. The high carbon sequestration and storage potential of healthy mangrove forests is now widely recognized as one of the main ecosystem services to be gained from restoring/rehabilitating and protecting mangroves[4-7].

There has been a long history of allocating concessions to permit logging of mangroves in Thailand, where previously 90% of the mangrove wood extracted was used to produce charcoal[8]. Until the 1960s, mangrove concessions operated on a 10-year felling cycle and a shelterwood system whereby only trees with a girth above 30 cm at breast height could be cut[9]. From 1969, the Government of Thailand introduced a new concession system with leases granted for 15 years. Nearly 177,000 ha of mangrove forest were allocated in 310 concession areas in the first cycle (1968-1983), with almost 88% of this area being in Ranong and other southern provinces. This was followed by almost 144,000 ha allocated in 248 concessions for the second cycle during the years 1986 to 1991, which was equivalent to almost 75% of the total mangrove forest area in the country[9]. In Ranong Province, for example, 19,573 ha of mangrove forest were under concession for charcoal production in 1990[10].

Forty mangrove forest management units were established to ensure that the concessionaires complied with the new silvicultural system (a rotation of 30 years with clear-felling of alternate strips of forest 40 meters wide on a 15-year cycle) and its regulations. However, some concessionaires did not follow the regulations and violations also included logging outside of concession areas[11,12]. In response to this situation, aggravated by mangrove degradation from tin mining, plus uncontrolled mangrove conversion to aquaculture and other land uses[13], the government approved various policies from the mid-1980s to promote mangrove conservation. These culminated in a Cabinet Decision in 1998 to end the issuing of new mangrove logging concessions and assign conservation status to most of the country's remaining mangrove forests[9].

The Government of Thailand also recognized the particular ecological and socio-economic importance of the Ranong mangrove ecosystem, which is the largest single expanse of mangrove forest in the country. The Royal Forest Department established a Mangrove Forest Research Center (MFRC) in Ngao Sub-district of Ranong in 1982. Then, in collaboration with UNESCO, a Biosphere Reserve covering 30,309 ha of Ranong's mangrove ecosystem (containing 10,148 ha of mangrove forest) was declared in 1997[14]. The MFRC and Ranong Biosphere Reserve (RBR) were transferred to the Department of Marine and Coastal Resources (DMCR) in 2002, which was two years after the last mangrove concession agreement in Ranong had ended.

In anticipation of the termination of mangrove exploitation for charcoal production in Thailand, and the establishment of a Biosphere Reserve in Ranong, a study on mangrove rehabilitation was initiated in 1994 at a former mangrove charcoal concession area within the proposed Biosphere Reserve. The objectives were to compare survival, growth and biomass gain by four of the dominant mangrove tree species in Ranong: *Rhizophora apiculata* (Ra), *R. mucronata* (Rm), *Bruguiera cylindrica* (Bc) and *Ceriops tagal* (Ct) when planted in single species blocks, and to monitor their development into forest habitat, which could then be compared with conserved areas of near-natural mixed species mangrove forest in other parts of the planned

Biosphere Reserve. *Rhizophora* and *Bruguiera* species were exploited heavily for charcoal production during the mangrove concession periods, while *Ceriops tag*al, which grows naturally in association with *Rhizophora* and *Bruguiera* trees in the RBR, was used for firewood and other various purposes such as tool-making.

In addition to annually monitoring survival and growth of the planted trees in the first four years, natural plant recruitment and the abundance and diversity of mangrove-associated macrofauna were recorded in 1999 as indicators of forest ecological function[15]. Following this detailed assessment of the forest habitat in each species block in 1999, the site remained protected by DMCR staff and was used for educational purposes. Further studies of the species blocks were made in 2008, 2019 and 2023 in order to obtain a long-term record of tree survival and growth for the purpose of comparing carbon fixation by the four planted species. As a further comparison, carbon storage in a mature, conserved mixed species forest in the RBR dominated by *Rhizophora apiculata* and *Ceriops tagal,* together with a smaller number of *Bruguiera*, *Xylocarpus* and other tree species, was also estimated in 2023.

EXPERIMENTAL

The study site was located on an elevated levee above the main waterway (Klong Ngao, a large, tidal estuary) that runs through the core area of the RBR [Figure 1]; the site was described in[15] as site 3. The site contained the stumps of felled trees removed by the concession holder and had a dense overgrowth of the invasive vine *Derris trifoliata* and the vine-like shrubs *Acanthus ilicifolius* and *Finlaysonia obovata*. These plants are regarded as weeds by Thai foresters and are strongly disliked because they impede natural mangrove regeneration[16]. In November 1994 the weed vegetation was cleared and nursery-reared seedlings of the four selected species were planted as monocultures in adjacent blocks with a spacing of 1.5 m × 1.5 m. This was a standard spacing adopted for these species in Thailand for both commercial wood production and mangrove rehabilitation[17].

Each species block comprised 35 to 40 rows of seedlings planted parallel to the estuary, with 30 seedlings per row. The *R. apiculata* and *R. mucronata* seedlings survived well, but the smaller *Bruguiera* and *Ceriops* seedlings died due to smothering by regrowth of *Acanthus*, *Derris* and *Finlaysonia*. These fast-growing weeds were cleared again and replacement *Bruguiera* and *Ceriops* seedlings were planted in November 1995. This time the seedlings were better protected by cutting back weed regrowth for several months until they were well-established and able to grow above the weed vegetation.

From 1995 to 1998 the height and stem girth of individually marked planted seedlings were recorded. In 1999 and again in 2008, 2019 and 2023, the planted mangroves were measured in a 10 m × 10 m quadrat positioned randomly within each species block and any recruited trees, saplings and seedlings were also recorded. Recruits were classified as saplings if they exceeded 1.5 m in height[18] and trees if their girth exceeded 4 cm[19]. Due to the presence of many understorey plants in some quadrats (mainly *Acanthus ilicifolius*, plus some *Finlaysonia obovata*), these were recorded only as abundant, few or none, and were not included in the estimates of mangrove plant biomass and carbon stock. Tree height was measured using a measuring pole extendable to eight meters. However, in 2019 and 2023 the planted trees greatly exceeded the height of the pole, so their height was estimated by eye by an experienced member of the DMCR fieldwork team. Tree girth at breast height (1.3 m), or at 20 cm above the tallest prop root in the case of *Rhizophora* trees, was recorded using a tape measure. The measurements were used to calculate diameter at breast height (DBH), basal area (BA) and plant biomass. Aboveground biomass (AGB) was calculated using the general regression equation of Komiyama *et al.*[20]:

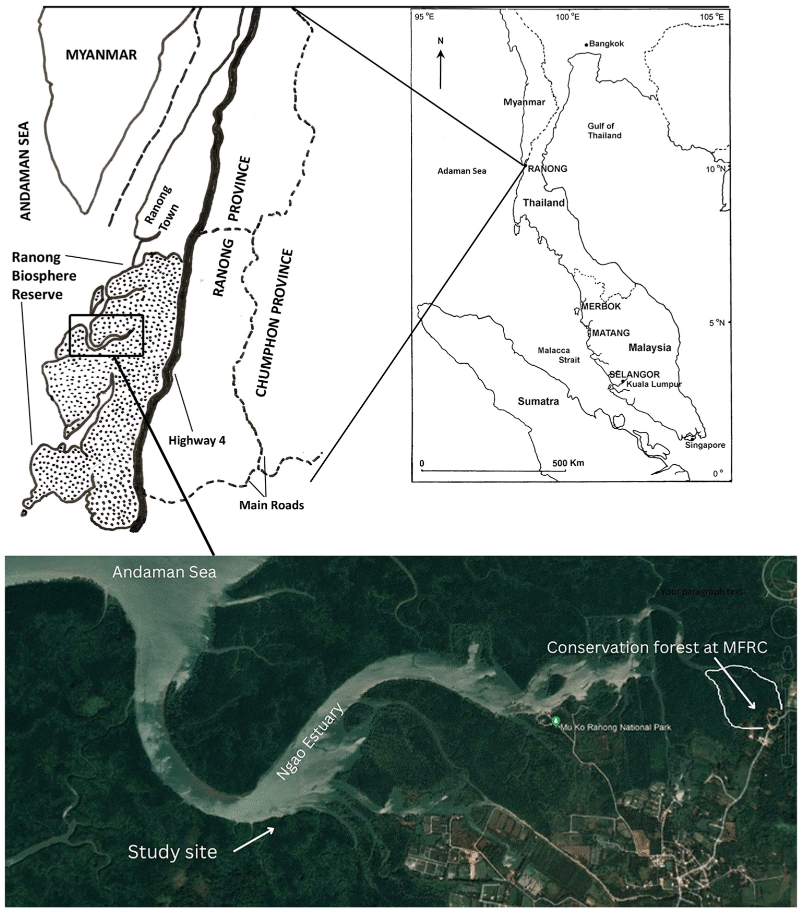

Figure 1. The location of the Ranong Biosphere Reserve in Ranong Province, southern Thailand, and the study sites on a former mangrove charcoal concession area and in a mixed species conservation forest area.

$AGB = 0.251\ \rho\ DBH^{2.46}$ (where ρ = wood density)

Komiyama *et al.* figures for wood density (Mg m^{-3}) were also used (Ra 0.770; Rm 0.701; Bc 0.749; Ct 0.746) because they are based on their study of mangrove trees in Ranong[20].

AGB was converted to a carbon equivalent value using the carbon to dry weight biomass ratios derived by[19] for trees in the RBR (*R. apiculata* 0.4728; *R. mucronata* 0.4774; *B. cylindrica* 0.4824; *C. tagal* 0.4935).

Below ground biomass (BGB) was calculated using the equation[20]:

$BGB = 0.199\ \rho^{0.899}\ DBH^{2.22}$

Belowground carbon content was calculated by multiplying BGB by 0.39, which is a median conversion factor for mangroves[21].

In 2023, four soil samples were collected randomly in each 100 m^2 quadrat from a depth of 30 cm. The soil samples were put into labeled, airtight plastic containers (volume 50 cm^3) and taken to the laboratory for analysis. This should be oven-drying (in pre-weighed dishes at 60 °C for about 72 h until no further loss in weight) to determine the water loss by evaporation. Soil moisture content was calculated as a percentage of wet mass and dry bulk density (g cm^{-3}) was determined from the mass of dried sample divided by the original volume. The dried soil samples were then homogenized using a mortar and pestle, then 2 g of each sample was placed in pre-weighed crucibles in a muffle furnace at 450 °C for 6 h. The percentage of soil organic carbon (SOC) was determined using the Loss on Ignition (LOI) method[21,22]. First the percentage of organic matter loss on ignition was calculated by dividing the difference in dry mass before and after combustion by the final dry mass and multiplying by 100. Then percentage SOC was calculated using the equation: % SOC = 0.415*% LOI + 2.89[23]. Percentage SOC extrapolated to Mg C ha^{-1} was compared between sites by one-way analysis of variance (ANOVA).

RESULTS AND DISCUSSION

Tree survival

Because the four mangrove species were planted at an equal spacing of 1.5 m × 1.5 m, it was possible to identify gaps in 2019 and 2023 where planted trees were missing and therefore presumed to have died at an early stage. Mature trees that had died were still standing, or the clear remains of former trees were still visible. In 2019 the number of planted trees surviving was highest for Ra (95%), followed by Ct (90%) and Bc (82%), whereas only two-thirds of the Rm trees survived [Table 1]. Compared to the survival rates in 2019, survival in 2023 was similar for Rm (71%) and Ct (84%), but the survival of Ra and Bc had decreased to 77% and 73%, respectively. Unfortunately, there had been significant illegal cutting of Bc since 2019. The cut trees were included as living trees when calculating survival, because these were healthy trees cut selectively at about 30 cm above the buttress roots in order to extract the main stem, which is straight and tall and valuable as pole wood for construction purposes. A small number of Ra trees had also been cut just above their highest prop root.

Living trees in the four species blocks were also counted in 100 m^2 quadrats in 1999[15]. The data indicate that most of the Rm tree losses occurred before 1999 (Rm survival ≤ 78% in 1999, compared to 67%-71% survival in 2019-2023). The lower survival rate of Rm is surprising because[16] reported that both Ra and Rm seedlings planted on a similar degraded site in the Ngao Estuary mangroves achieved 90% survival after one year, compared to only 70% survival for Bc seedlings. One possible explanation is predation of Rm seedlings by leaf-eating crabs as it was noted that the Rm block contained numerous sesarmid crab holes and, by observation, fallen Rm leaves were consumed more by crabs than were leaves of the other three tree species. Some sesarmid species have been observed to feed directly on *Rhizophora* seedlings[24] and crab damage was blamed for the death of mangrove seedlings in growth experiments in Ranong Province[25].

Tree growth

Growth of the four mangrove species from 1995 to 2023 is compared in Figure 2 and their average height, diameter at breast height (DBH) and Basal Area (BA) are shown in Table 2. The mean annual diameter growth rates were: Ra 0.29 cm, Rm 0.43 cm, Bc 0.23 cm and Ct 0.34 cm. These are similar to mean annual growth rates reported in Malaysia[26] for Ra (0.32 cm) and Bc (0.22 cm).

There was an apparent decrease in average height of the Rm and Bc trees from 2019 to 2023 and the BA of the trees also decreased, except in the Ct block [Figure 3]. However, BA in the Ct and Rm blocks exceeded that in the conservation forest by 2023. Coupled with tree mortality in the species blocks in 2023 [Table 1], it is likely that the growth data indicate the occurrence of natural, or self-thinning, which is a well-established response to increased competition as trees grow and become more crowded[27]. Self-thinning as a cause of high tree mortality has been reported in Thailand among Ra trees 16 years after planting at the same 1.5 m × 1.5 m spacing as in the present study[28]. In Malaysia, it accounted for 43% and 29% mortality in densely planted 13- and 18-year *Rhizophora* plantations, respectively[29].

Table 1. The number of living, dead/missing and cut trees recorded in the planted species blocks in 2019 and 2023

Species	All trees	Living trees	Dead/missing trees	Cut trees	Survival (%)
2019: Number of trees in 100 m^2 quadrat					
R. apiculata (Ra)	40 (+ 1)*	38 (+ 1)*	2	0	95
R. mucronata (Rm)	48	32	16	0	67
B. cylindrica (Bc)	49	40	9	0	82
C. tagal (Ct)	49	44	5	0	90
2023: Number of trees in 100 m^2 quadrat					
R. apiculata (Ra)	43	32	10	1	77**
R. mucronata (Rm)	42	30	12	0	71
B. cylindrica (Bc)	49	27	13	9	73**
C. tagal (Ct)	49	41	8	0	84

*The *R. apiculata* quadrat sampled in 2019 contained one *B. parviflora* tree. Survival (%) is calculated for *R. apiculata* only; **Cut trees are included in the calculations of survival (%).

Table 2. Mean height and diameter at breast height (DBH) ± standard deviation, and basal area (BA) of trees extrapolated to m^2 per hectare, in the four planted species blocks and mixed species conservation forest in the RBR

Year and species[1]	Height (cm)	DBH (cm)	Basal area (m^2 ha^{-1})
1999			
Ra	319 ± 31.5	2.69 ± 0.52	2.59
Rm	399 ± 76.5	3.44 ± 0.89	3.77
Bc	131 ± 36.6	1.82 ± 0.83	0.87
Ct	145 ± 21.4	2.43 ± 0.63	2.36
Mixed species conservation forest	894 ± 477	9.02 ± 9.34	43.03
2008			
Ra	1,074 ± 288	7.56 ± 1.89	20.05
Rm	1,291 ± 163	10.10 ± 2.56	33.28
Bc	500 ± 2.39	5.20 ± 1.79	14.98
Ct	492 ± 48.7	6.35 ± 2.38	29.41
2019			
Ra	1,205 ± 375	7.92 ± 2.66	32.34
Rm	1,963 ± 228	9.08 ± 6.89	49.60
Bc	1,292 ± 94.5	7.47 ± 3.43	33.35
Ct	1,224 ± 56.8	8.63 ± 3.37	38.34
2023			
Ra	1,356 ± 266	8.37 ± 2.68	27.36
Rm	1,719 ± 225	12.32 ± 2.13	38.15
Bc	1,049 ± 261	6.39 ± 2.97	19.45
Ct	1,214 ± 95.7	9.39 ± 2.20	40.88
Mixed species conservation forest	1,741 ± 671	15.12 ± 7.34	35.68

[1]Ra and Rm trees planted in 1994; Bc and Ct trees planted in 1995.

The tree growth data may also have been affected by the tree-cutting observed in the Ra and Bc blocks in 2023. The outbreak of COVID-19 in 2020 created great hardship in Thailand, as in other countries, and we conclude that this may have been the reason why the first instance of tree-cutting in the species blocks occurred between 2019 and 2023. Despite this incident, however, there has been a long history of successful community cooperation in mangrove conservation in the RBR and elsewhere in Thailand[30].

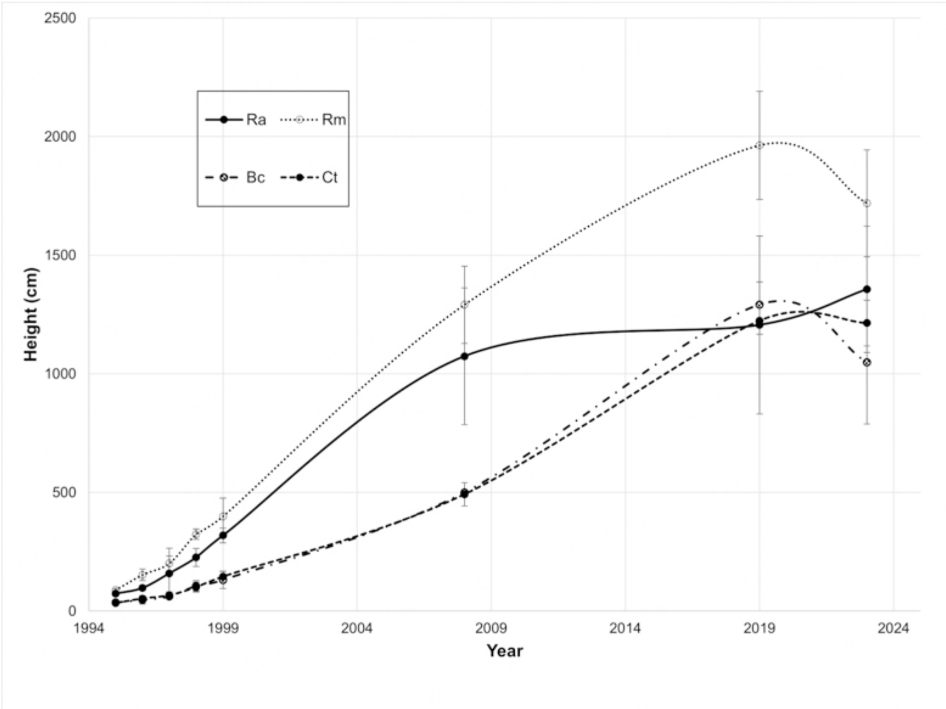

Figure 2. Mean tree height for each mangrove species over the study period.

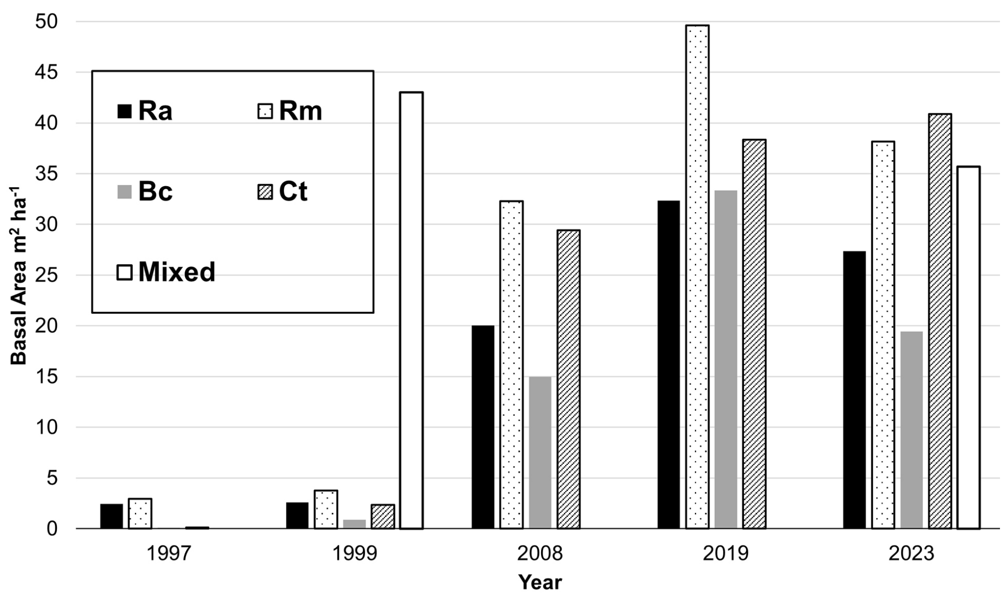

Figure 3. Basal area in each species block and in the mixed species conservation forest.

Rotation in the clear-felling charcoal concession system in Thailand was fixed at 30 years so that Ra and Rm (the target species) could reach the preferred stem diameter for charcoal-making of 15-20 cm[11,31], which was considered achievable within 30 years. However, after 29 years, many of the planted Ra trees and some of the Rm trees were below 10 cm diameter (Table 2: Ra 8.4 ± 2.68; Rm 12.3 ± 2.13). This explains the primary reason why mangrove exploitation for charcoal in southern Thailand was not sustainable. Studies by[10] in Ranong after the first concession period confirmed that regrowth of the mangrove forest in Ranong could not meet the expected wood harvest and demand for charcoal. Only 18% of the total concession area in southern Thailand was replanted[9], and not always with good success[11]. The result was that charcoal production in the second concession period declined and mangroves in many concession areas remained degraded, leading to the Government of Thailand's decision to end mangrove logging concessions in 1998.

Natural recruitment

Tables 3 and 4 show the number of mangrove saplings and seedlings recorded in the four planted species blocks in 2019 and 2023, respectively. Very few saplings had developed by 2019 and in total within all four 100 m^2 quadrat samples only two Bc saplings, two Bp saplings and one Ct sapling were recorded [Table 3]. However, there were numerous *Bruguiera* seedlings in the Bc and Ra quadrats (179 Bc seedlings and 370 Bp seedlings, respectively). The finding of so many Bp seedlings in the Ra block in 2019 can be explained by the presence of a mature Bp tree in the Ra quadrat (height 18 m, DBH 13 cm), which must have recruited into the Ra block many years earlier. *Bruguiera* trees are known to have highly effective recruitment capabilities and seedlings can establish by both self-planting and stranding strategies[32,33]. The former strategy was evident from the large number of *Bruguiera* seedlings in the vicinity of mature *Bruguiera* trees in the Ra and Bc sampled quadrats. (It was noted in July 1999 that more than 80% of the Bc trees in the 100 m^2 quadrat sample were already flowering and fruiting, even though they were less than 2 m tall). Similarly[19], reported high densities of Bp and Bc seedlings equivalent to 21,660 ha^{-1} and 822 ha^{-1}, respectively, in a mature, mixed species forest in the RBR. Nineteen Rm seedlings had also recruited via self-planting in the 100 m^2 Rm quadrat by 2019.

The pattern of mangrove recruitment in the four species blocks had changed significantly by 2023 with the presence of saplings and seedlings of several other species recorded in the sampled quadrats [Table 4]. *Xylocarpus granatum* saplings and seedlings were recorded in the *Rhizophora* sampled quadrats, as well as Ct seedlings, indicating that propagules of these two species had been carried into the *Rhizophora* blocks by high tides (stranding strategy). The dense carpeting of Bc seedlings recorded in the Bc block in 2019 resulted in many saplings of this species in 2023 (almost one sapling per m^2). The low rates of recruitment of Ra and Rm seedlings, even by 2023 [Table 4], could be due to the extremely high abortion rates during flower bud development and anthesis reported for these species in Ranong[34] and elsewhere in Thailand[35].

The 100 m^2 sampled quadrats in the Ct block differed from those containing the other three planted species in having no recruits or undergrowth species in 2019 and only Ct seedlings in 2023. The latter were numerous (almost one seedling per 2 m^2) and had clearly recruited from the planted Ct trees. When measured in 1999 by[15], the Ct block was at a slightly lower intertidal level (2.99 m above extreme low water mark) compared to the other species blocks (3.19-3.27 m). Thus, there was at least the same potential for other mangrove species to be transported tidally into the Ct block as elsewhere in the study site.

In the mixed species conservation forest eight tall Ct saplings were recorded in the sampled 100 m^2 quadrat, together with nine Ra seedlings, showing that Ct seedlings can recruit and grow well within mature, *Rhizophora*-dominated forest areas. Together with *Bruguiera* and *Xylocarpus* species, *Rhizophora* and *Ceriops* trees form the main mangrove assemblage in the upper intertidal zone of the RBR, while *Sonneratia -Avicennia* and *Aegiceras* assemblages occupy the lower intertidal areas[36].

Mangrove biomass and carbon stock

As expected, the two *Rhizophora* species showed the greatest biomass gain over the study period of 29 years [Table 5]. However, the unit area biomass of Ct trees exceeded that of the Ra trees in 2008 and 2019 before

Table 3. Natural recruitment of mangrove species in the four species blocks in 2019

Species block	Mangrove recruits	Ra	Rm	Bc	Ct	Bp	Ao	Xg	Topography and undergrowth species
Ra	Saplings			1		1			*Acanthus ilicifolius*
	Seedlings					370		8	
Rm	Saplings				1	1			*Acanthus ilicifolius*
	Seedlings		19			2		5	
Bc	Saplings			1					Some mud lobster mounds; *Acanthus*, Fo
	Seedlings			179				1	
Ct	Saplings								Many mud lobster mounds; no undergrowth
	Seedlings								

Saplings identified as mangrove recruits exceeding 1.5 m in height. Ra: *Rhizophora apiculata*; Rm: *Rhizophora mucronata*; Bc: *Bruguiera cylindrica*; Ct: *Ceriops tagal*; Bp: *Bruguiera parviflora*; Ao: *Avicennia officinalis*; Xg: *Xylocarpus granatum*; Fo: *Finlaysonia obovata*.

Table 4. Natural recruitment of mangrove species in the four species blocks in 2023

Species block	Mangrove recruits	Ra	Rm	Bc	Ct	Bp	Ao	Xg	Topography and undergrowth species
Ra	Saplings							7	Abundant *Acanthus*
	Seedlings	4			6	15		3	
Rm	Saplings		1	1		3		1	Abundant *Acanthus*
	Seedlings		8			4			
Bc	Saplings			92			1		Some mud lobster mounds; no undergrowth
	Seedlings			7					
Ct	Saplings								Many mud lobster mounds; no undergrowth
	Seedlings				47				
Mixed species conservation forest	Saplings				8				Some mud lobster mounds; no undergrowth
	Seedlings	9							

Saplings identified as mangrove recruits exceeding 1.5 m in height. Ra: *Rhizophora apiculata*; Rm: *R. mucronata*; Bc: *Bruguiera cylindrica*; Ct: *Ceriops tagal*; Bp: *Bruguiera parviflora*; Ao: *Avicennia officinalis*; Xg: *Xylocarpus granatum*.

declining relative to the forest biomass of the *Rhizophora* species by 2023 (Ra 279 Mg ha^{-1}, Rm 400 Mg ha^{-1}, Ct 187 Mg ha^{-1}).

The 1999 and 2023 estimates of 492 and 470 Mg ha^{-1}, respectively, for the *Rhizophora*-dominated mixed species conservation forest, where no trees have been felled for at least 45 years[34], indicate that the planted Ra and Rm trees still have the potential to grow significantly larger. But this seems not to be the case for the planted Bc trees, which suffered considerable die-back (possibly aggravated by the illegal cutting of many Bc stems), resulting in a net decline in the estimated living biomass per unit area. However, the presence of many Bc seedlings in 2019 and saplings in 2023 [Tables 3 and 4] confirms that this species has a strong compensatory mechanism in the form of mass production of propagules and self-planting seedling recruitment[33]. This trend may also have commenced in the Ct planted block, because tree survival declined by 6% from 2019 to 2023 and numerous seedlings of this species were present in the 2023 sampled quadrat [Table 4].

Mangrove biomass and carbon estimates for primary and secondary mangrove forests on the Andaman coast of southern Myanmar and Thailand, together with two studies of Ra plantations or regrowth forest of known ages on the Gulf of Thailand coast[37,38], are compared with those from the present study in Table 6. Early estimates of mangrove biomass in the RBR of 571 Mg ha^{-1} for primary *Rhizophora*-dominated forest[39] and 399 Mg ha^{-1} for mixed *Rhizophora*-*Bruguiera* forest[31] are consistent with reported values of 426 and

Table 5. Aboveground and belowground living biomass in the four planted species blocks and mixed species conservation forest in the Ranong Biosphere Reserve

Year and species[1]	AGB kg/100 m^2	BGB kg/100 m^2	Total biomass equivalent Mg ha^{-1}
1999			
Ra	103.3	71.1	17.4
Rm	155.8	92.9	24.9
Bc	31.6	20.7	5.2
Ct	88.8	57.1	14.6
Mixed species conservation forest	3,576.8	1,342.5	491.9
2008			
Ra	1,233.2	626.9	186.0
Rm	2,258.3	1,038.8	329.7
Bc	829.3	436.3	126.6
Ct	1,801.2	897.6	269.9
2019			
Ra	2,210.1	1,053.3	326.3
Rm	3,833.1	1,648.5	548.2
Bc	1,897.8	916.6	281.4
Ct	2,648.0	1,240.7	388.9
2023			
Ra	1,894.6	897.4	279.2
Rm	2,767.7	1,230.1	399.8
Bc	1,177.8	589.3	176.7
Ct	1,276.7	592.8	186.9
Mixed species conservation forest	3,364.1	1,335.9	470.0

Ra: *Rhizophora apiculata*; Rm: *R. mucronata*; Bc: *Bruguiera cylindrica*; Ct: *Ceriops tagal.* [1]Ra and Rm trees planted in 1994; Bc and Ct trees planted in 1995.

626 Mg ha^{-1} for *R. apiculata* and *R. mucronata* primary forests, respectively, on Lampi Island in Myanmar's Tanintharyi Region, which borders Ranong[40]. Death of some of the largest trees, plus illegal felling, has reduced the primary forest biomass in parts of the RBR[19]. More recently, the estimate for primary mixed forest in one of the RBR core areas was 363 Mg ha^{-1}[41]. Overall, primary mangrove forest is now extremely rare in both Myanmar and Thailand. Almost all the mangroves along the Andaman coast today are second-growth forests resulting from a combination of natural regeneration and mangrove planting. The biomass values of 492 and 470 Mg ha^{-1} recorded in the RBR mixed species conservation forest in 1999 and 2023, respectively (this study), highlight the need to protect the few remaining areas of near-primary mangrove forest. As indicated in Table 6, biomass accumulation in mangrove plantations is closely correlated with planting density, species and age of the planted trees. After almost 29 years of growth, the biomass estimates for the Ra and Rm planted forest blocks (equivalent to 279 and 400 Mg ha^{-1} respectively) are consistent with 345 Mg ha^{-1} reported for a mature *Rhizophora*-dominated forest in Samsukran District of Ranong Province[42], but higher than the total biomass of 211 Mg ha^{-1} for Ra in a 28-year-old plantation in Malaysia[43]. The estimated biomass in the Ct forest block (187 Mg ha^{-1}) is similar to 180 Mg ha^{-1} reported for secondary Ct forest in Satun, southern Thailand[44,45].

Soil analysis

Estuarine mangrove clay-loam soils are generally rich in organic matter[46] and this is the case within the Ngao Estuary. Although soil organic content (SOC) was not measured at the study site before the four species were planted, a comparable mangrove concession area on the opposite bank of the estuary was

Table 6. Estimates of mangrove biomass and carbon stock in primary, secondary and plantation forests in Thailand and southern Myanmar

Country and location	Forest type and dominant species	a. Mean tree density b. Mean tree height c. Mean basal area	AGB Mg ha^{-1}	BGB Mg ha^{-1}	Total Mg ha^{-1}	Carbon Mg ha^{-1}	Reference
Thailand: Ranong Biosphere Reserve	Primary forest, *Rhizophora apiculata and Bruguiera*-dominated	a. 1,246 ha^{-1} b. 10.6 m c. 24.0 m^2/ha^{-1}	281.2	117.6	398.8	190.2*	[31]
Thailand: Ranong Biosphere Reserve	Primary forest, *Rhizophora*-dominated	a. nd b. nd c. 31.3 m^2/ha^{-1}	298.5	272.9	571.4	272.5*	[39,45]
Myanmar: Lampi Island, Tanintharyi	Primary forest, *Rhizophora apiculata*-dominated	a. 465 (+ 980) ha^{-1} b. 16.0 m c. 31.8 m^2/ha^{-1}	466.8	159.6	626.4	298.8*	[40]
Myanmar: Lampi Island, Tanintharyi	Primary forest, *Rhizophora mucronata*-dominated	a. 474 (+ 320) ha^{-1} b. 13.9 m c. 23.2 m^2/ha^{-1}	314.6	111.6	426.2	203.3*	[40]
Thailand: Ranong Biosphere Reserve	Primary mixed forest, with eight mangrove species	a.856 (+ 44) ha^{-1} b. 20.3 m c. 28.7 m^2/ha^{-1}	328.3	34.95	363.3	173.4*	[41]
Thailand: Ranong Samsukran District	Mature forest, mixed species *Rhizophora*-dominated	a. 1,313 ha^{-1} b. nd c. 25.0 m^2/ha^{-1}	250	95	345	155	[42]
Thailand: Ranong Biosphere Reserve	Mature forest, mixed species, *Rhizophora* and *Ceriops*-dominated	a. 2,400 ha^{-1} b. 17.4 m c. 35.7 m^2/ha^{-1}	336.4	133.6	470.0	212.1***	This study
Thailand: Ranong Biosphere Reserve	Mixed forest, with 17 mangrove species	a. 1,905 (+ 1,105) ha^{-1} b. 12.05 m c. nd	119.8	nd	166.5	79.4***	[19]
Thailand: Ranong Biosphere Reserve	Secondary mixed forest, with nine species	a.1,286 (+ 152) ha^{-1} b.17.05 m c. 25.1 m^2/ha^{-1}	258.3	30.9	289.2	138.0	[41]
Thailand: Satun	Secondary forest, *Ceriops tagal*-dominated	a. nd b. 5.2 m c. 15.2 m^2/ha^{-1}	92.2	87.5	179.7	85.7**	[44]
Thailand: Phuket Island	*Rhizophora apiculata*, 15 years old regrowth after felling	a. nd b. 8.0 m c. nd	159	62	221	105.4*	[35]
Gulf of Thailand: Samut Songkram	12-year-old *Rhizophora apiculata* plantation for charcoal production	a. 22,089 ha^{-1} at 8-10 years b. 11.4 m c. 20.2 m^2/ha^{-1}	298.9	59.8	140.5	169	[37]
Gulf of Thailand: Chumphon	*Rhizophora apiculata* forest regrowth after partial clear-felling 15 years earlier	a. 5,402 ha^{-1} b. nd	344.2	352.7	696.9	332.5*	[38]

		c. 33.3 m^2/ha^{-1}					
Gulf of Thailand: Chumphon	*Rhizophora apiculata* plantation of 3-year-old trees in an abandoned shrimp pond	a. 13,212 ha^{-1} b. nd c. 34.7 m^2/ha^{-1}	65.4	269.9	335.3	159.9*	[38]
Thailand: Ranong Biosphere Reserve	29-year-old *Rhizophora apiculata* plantation on a former charcoal concession site	a. 3,100 ha^{-1} b. 13.6 m c. 27.4 m^2/ha^{-1}	189.5	89.7	279.2	124.6***	This study
Thailand: Ranong Biosphere Reserve	29-year-old *Rhizophora mucronata* plantation on a former charcoal concession site	a. 3,000 (+ 100) ha^{-1} b. 17.2 m c. 38.2 m^2/ha^{-1}	276.7	123.1	400.0	180.1***	This study
Thailand: Ranong Biosphere Reserve	28-year-old *Bruguiera cylindrica* plantation on a former charcoal concession site	a. 2,700 (+ 9,200) ha^{-1} b. 10.5 m c. 19.5 m^2/ha^{-1}	117.8	58.9	176.7	79.8***	This study
Thailand: Ranong Biosphere Reserve	28-year-old *Ceriops tagal* plantation on a former charcoal concession site	a. 4,200 ha^{-1} b. 12.1 m c. 40.9 m^2/ha^{-1}	127.7	59.3	186.9	86.1***	This study

Tree density data shown for[19,40,41] and this study include both trees and saplings (in brackets), but not seedlings. nd: no data; *Based on an average carbon to biomass ratio of 0.477[19], if not specified; and BG carbon: BGB × 0.39[34]; **BGB: living plant biomass only; ***AGB converted to AG carbon using species-specific conversion factors[19].

reported to have an organic content of 7.4%-11.3% in the upper 20 cm layer at a distance of three to 100 m from the bank[34]. The same study also found that SOC increased with depth and was up to 23% at a depth of 50 to 100 cm as a result of long-term accumulation of sediment and organic matter in the former primary mangrove forest. When measured in 2023 [Table 7], SOC at a depth of 30 cm in the four species blocks was similar (7.8%-8.3%) and only slightly lower (and not significantly different $P = 0.4$) to that in the mature conservation forest (8.5%). However, there could be an overestimation of organic carbon content because the % LOI method could also lose inorganic carbon and structural water. In soils containing > 11% clay minerals, a significant amount of structural water (water not lost by heating at 60 °C) may be driven off during heating at 450 °C[47]. The RBR estuarine soils are generally firm and highly cohesive with a fine texture due to their high clay and silt content (above 75%) in the upper layer[34]. However, the Ct soil samples were noticeably different from those from the other species blocks by their color, texture and higher soil C, suggesting the possible presence of inorganic carbon. Further studies on the plantation soils are merited, including on soil texture and bioturbation, because there was also considerable in-soil activity by mud lobsters in the Ct forest block in the form of burrow mound-building.

The felling and removal of mangrove trees during the concession periods created a considerable amount of habitat disturbance, but the trees were cut manually above ground level so it is reasonable to assume that any loss of soil carbon was confined to the upper 10-20 cm layer. A common complaint levied at the concessionaires was that, in order to save time, they did not cut the trees as close to the ground as they were supposed to. Thus, it can be concluded that the large concentrations of deep soil carbon in the Ngao Estuary mangroves, including in the plantation study site, have not been disturbed by wood extraction for charcoal; and that organic matter from the planted mangroves has compensated for any carbon losses from the near-surface soil layer during the former concession periods, and when planting the seedlings.

Table 7. Analysis of soils from 30 cm depth in each planted species block (± SD) and in the mixed species conservation forest in March 2023

Species	Soil moisture (%)	Bulk density ($g\ cm^{-3}$)	Organic carbon (%)	Soil carbon density ($g\ cm^{-3}$)	Soil carbon ($Mg\ C\ ha^{-1}$)
Rhizophora apiculata	47.20 ± 2.35	0.67 ± 0.10	7.80 ± 0.43	0.0525 ± 1.07	525 ± 107
R. mucronata	45.11 ± 2.14	0.72 ± 0.05	7.82 ± 0.46	0.0566 ± 0.44	566 ± 44
Bruguiera cylindrica	42.96 ± 1.22	0.85 ± 0.05	8.00 ± 0.40	0.0680 ± 0.35	680 ± 35
Ceriops tagal	42.48 ± 0.87	0.90 ± 0.04	8.30 ± 0.12	0.0743 ± 0.31	743 ± 31
Mixed species conservation forest	49.63 ± 2.68	0.72 ± 0.05	8.54 ± 0.99	0.0616 ± 0.91	616 ± 91

Ecosystem carbon

The global average carbon (C) concentration in mangrove forest soils of all types estimated by[48] is 361 Mg C ha^{-1} ± 136 (SD). Based on soil C measurements in 28 countries[6], calculated that the mean SOC in carbon-rich mangroves is 703 ± 38 Mg C ha^{-1}. The mean estimates for soil C in the planted species blocks (525 to 743 Mg C ha^{-1}) and mixed species conservation forest (616 Mg C ha^{-1}) are consistent with these global studies [Table 7]. When the mangrove vegetation and SOC estimates are combined, the values for mangrove ecosystem C are 650 to 829 Mg C ha^{-1} for the four species forest blocks and 828 Mg C ha^{-1} for the mixed species conservation forest [Figure 4]. A similar estimate of 719-802 Mg C ha^{-1} was reported from the Mekong Delta for mangroves in Mui Ca Mau National Park[49], while for planted mangroves in the Can Gio Mangrove Biosphere Reserve the average figure was higher (889 Mg C ha^{-1}), but this included soil carbon measured to a depth of 3 m[50].

Mangrove soil C contributed 74%-90% of the total ecosystem C in the present study. This is consistent with an assessment of 10 estuarine mangrove forest sites across the Indo-Pacific region showing that soil C accounted for 71%-98% of ecosystem C[51]. The present estimates of mangrove ecosystem C are conservative because they include only C stocks in the upper 100 cm soil layer based on analysis of soil samples from 30 cm depth. Since soil C concentrations in the Ngao Estuary mangroves are greater below 30 cm depth[34], and estuarine mangrove organic matter can build up in soils to a depth of 3 m or more[50] due to sediment accumulation by mangroves over long time periods, resulting in deep, organically-rich soils, total ecosystem C in the Ngao Estuary mangroves must be at least as high as the mean for Indo-Pacific estuarine mangroves[51] of 1,074 Mg C ha^{-1}.

The average ecosystem C stock in rehabilitated mangroves 35 years after planting (mainly *R. apiculata*) in Can Gio[50] was not significantly different to that of naturally regenerated forests (889 ± 111 Mg C ha^{-1} and 844 ± 58 Mg C ha^{-1}, respectively), suggesting that after 35 years both planted and naturally regenerated mangroves stored similar levels of ecosystem C. Much the same outcome is predicted for rehabilitated and regenerated mangroves in the RBR. In 2023, 28-29 years after planting, ecosystem C in the four mangrove species blocks was on average only 9% less than that in the mixed species conservation forest.

CONCLUSION

Our estimates of living aboveground biomass and ecosystem C are consistent with other studies of planted mangroves where Ra is the dominant species, but 19%-36% below the average of 1,023 Mg C ha^{-1} for mangroves in the Indo-Pacific region[51]. However, our estimates for ecosystem C are conservative because they do not include dead trees, wood debris or leaf litter, or SOC below 1 m depth.

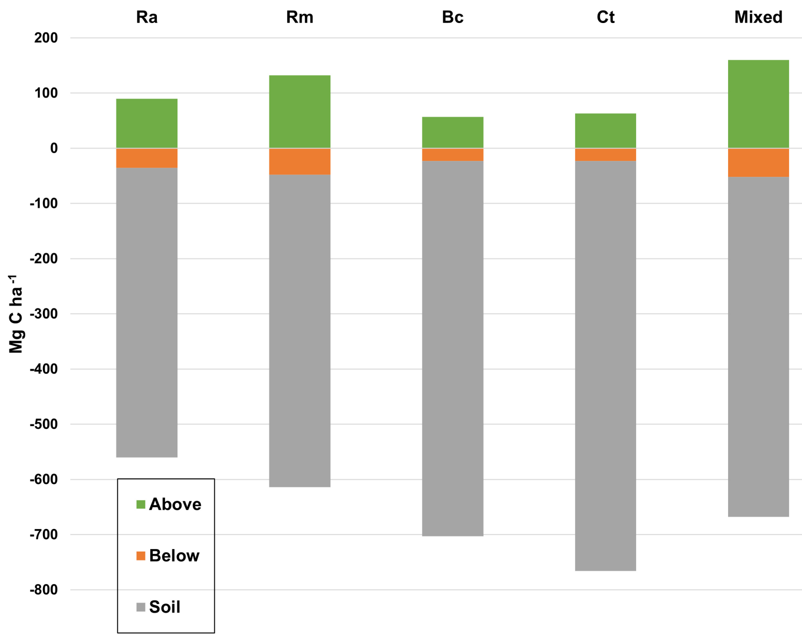

Figure 4. Above and below ground carbon and soil carbon Mg C ha^{-1} for each of the monoculture species blocks and mixed species conservation forest in 2023.

The RBR has been a notable success in terms of mangrove conservation. However, outstanding questions remain as to whether rehabilitated mangroves can reach the same levels of ecological function as natural mangrove forests, including C sequestration and storage, and biodiversity support; and if so, what time frame and other enabling factors are required? The findings confirm the importance of conserving the few remaining areas of near-primary mangrove forest in this region.

Based on the results from this study, we conclude that planting mainly *Rhizophor*a seedlings, together with a small number of *Bruguiera* and *Ceriops* seedlings to aid natural recruitment, and habitat and species diversity, would be an effective way to rehabilitate heavily degraded mangroves in the upper intertidal zone of estuaries such as the Ngao Estuary in Ranong. We also suggest that for conservation purposes, and to achieve higher survival, growth and mangrove C stocks, tree spacing of less than the standard 1.5 m × 1.5 m should be experimented with, especially for *Rhizophora* and *Bruguiera* species. A lower planting density may also facilitate recruitment by other mangrove species, with the desirable outcome of benefiting both carbon sequestration and biodiversity.

Because there are also former tin mining and shrimp farming sites in the RBR[15], it would be instructive from a forest management viewpoint to make further comparisons between naturally regenerating and planted mangroves in these previously exploited areas. Tin mining and shrimp farming in the Ranong mangroves caused not only mangrove deforestation but also substantial, and in the case of tin mining complete, removal of the mangrove soil.

DECLARATIONS

Acknowledgments

We are grateful to the Royal Forest Department, Department of Marine and Coastal Resources (DMCR) and former National Research Council of Thailand for facilitating our research in the RBR. The fieldwork would not have been possible without the invaluable cooperation and logistical support provided by the current Director of the MFRC, Mr. Khayai Thongnunui, and two former directors: Dr. Wijarn Meepol and Mr. Sophon Havanon. We are also grateful for the advice and assistance provided by Dr. Sonjai Havanond and Ms. Poonsri Wanthongchai in DMCR. The support of Mr Hakon Jalk for field data collection and analysis in the period 1996-1999 is also acknowledged, together with information management and other support provided by Mr Thomas Nielsen throughout this study. We also thank the many local people who helped us with the fieldwork, especially Messrs. Dusadee and Peh who planted the seedlings in the study site, and Keat, Kob, Mee, Jame and Rak who helped us to measure the trees in the sampled quadrats and collect soil and other samples. Queen's University Belfast Marine Laboratory Portaferry kindly provided laboratory facilities for analyzing the mangrove soil samples.

Authors contributions
Macintosh DJ selected the study sites and supervised site preparation and planting of mangrove seedlings. He sampled the planted mangroves in 2019 and 2023 and collected soil samples in 2023. He developed the main text of the manuscript and prepared the site location map.
Ashton EC sampled the planted mangroves in 1999 and 2008. She analyzed the 2023 mangrove soil samples, prepared the Tables and Figures in the manuscript, and contributed to text development and editing.

Availability of data and materials
All data used for this research are available from the authors, with permission from DMCR.

Financial support and sponsorship
This research was funded by Contract No. TS3-CT92-1052 awarded to the University of Stirling, Scotland by the European Community Science and Technology for Development Programme (STD-3); and a grant from the Danish Cooperation for Environment and Development (DANCED) program awarded to the University of Aarhus, Denmark for Danish-SE Asia Collaboration in Tropical Ecosystems Research and Training (Ref. No. 1230324).

Conflicts of interest
Both authors declared that there are no conflicts of interest.

Ethical approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

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