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Mangrove Productivity Estimation using Modelling Approach and Tree Parameters Assessment

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Abstract

This study used productivity models and above ground biomass to investigate productivity in different sites of MMFR. Ninety *Rhizophora apiculata* leaf samples were collected from different compartments (18, 31, 71, 74, 42 and 55) based on tree age and management. For biomass calculation, tree height and diameter were measured in plot of 10m x 10m in compartment 18, 31, 71, 74 and 67. The age of the trees were as follows: compartment 18 and 31 with 15-year-old, compartment 71 and 74 with 25-year-old and compartment 67 with 30-year-old mangrove trees. Compartment 42 and 55 are classified as virgin jungle reserve (VJR). Compartment 67 was not taken as a sample site due to technical reason and compartments in VJR were not considered for biomass estimation. Sixteen variables; stable isotopes (δ13C, δ15N), macronutrients (C, N, P), cations (Ca, Mg, Na, K) and trace elements (Cd, Cu, Fe, Mn, Pb, Zn) were analyzed. Productivity models and calculated biomass for investigated compartments showed similar trends. In 15-year age group; compartment 18 showed higher productivity than in 31. For the 25-year age group; compartment 74 had higher productivity than 71. No prominent increase was observed in biomass between 15-year old and 30-year old trees. Furthermore, with moderate N and δ15N loading input, compartments showed more productivity. The results conclude that MMFR is a sustainably managed mangrove forest and its productivity could be monitored using nutrient productivity models.

Keywords

MMFR, nutrients, *Rhizophora apiculata*, productivity models, biomass

Introduction

Tropical and subtropical coastlines are dominated by mangrove ecosystem. It is considered as one of the most productive ecological zone (Goessens et al., 2014). The productivity of mangroves depends on biotic and abiotic factors, with nutrients playing a key role. According to Ukpong (1997), the results from a study in Calabar River Nigeria, nutrient deficiency was one of the main factors which reduced the growth of mangrove forest. Nutrient availability is an essential factor in limiting mangrove productivity (Boto & Wellington, 1984; Feller, Whigham, McKee, & Lovelock, 2003; Onuf, Teal, & Valiela, 1977). Availability of nutrients varies hugely from site to site (Reef, Feller, & Lovelock, 2010). Soil is considered as storage pool of nutrients for mangroves (Alongi, Clough, Dixon, & Tirendi, 2003). In addition to that, mangrove leaf chemistry gives insight into mangrove dynamics and helps to track the growth in response to nutrients (Fry & Cormier, 2011).

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In the past few decades, a decline in productivity of Matang Mangrove Forest Reserve (MMFR) has been observed (Ellison, 2008). In Hawaiian island Florida, *Rhizophora mangle L* species was introduced 100 years ago. To find out the productivity of this untouched forest, following productivity models were applied (Fry & Cormier, 2011).

$$\text{Productivity} = \delta 13\text{C} \times \text{nutrients}$$

(Fry & Cormier, 2011)

$$\text{Productivity} = \text{salt} \times \text{nutrients}$$

Mangrove leaf nutrients analysis was used for these models, where N and P were used as growth-limiting nutrients. Sodium (Na) represented salinity and δ13C depicted fresh water use efficiency. In this study, these productivity models were applied to selected compartments of MMFR. For validation, models' results were compared with measured aboveground biomass (AGB) of the same compartment. The objective of this study is to investigate the productivity decline by applying and comparing the aforementioned productivity models. Sixteen variables: stable isotopes (δ13C and δ15N), macronutrients (C, N, and P), cations (Ca, Mg, Na, and K), and trace elements (Cd, Cu, Fe, Mn, Pb and Zn) were analyzed to achieve the results.

Methods

Study Site

MMFR is situated in Perak, Peninsular Malaysia expanding over an area of approximately 40,466 (Jusoff and Taha, 2008). It has been conserved and managed since early 20th century by Perak Forestry Department. The forest reserve is managed by smaller unit area of compartments. Apart from several compartments being virgin forest, the rest of the compartments are systematically planted with mangrove trees for charcoal production. The compartments used for timber extraction and supervised yearly are called managed compartments. In contrast, the compartments which are untouched for more than 80 years are called virgin jungle reserve (VJR). Trees of *Rhizophora apiculata* is the dominant species, around 85% from total trees in MMFR.

Seven compartments 18, 31, 71, 74, 42, 55, and 67 were selected for this study. Compartment selection was based on age and management. Compartments 18 and 31 have trees with the age of 15 years, 71 and 74 with 25 years, 67 with 30 years, and 42 and 55 are VJR. In MMFR, Compartments 18, 31, and 42 are from the same area of Kuala Sepetang, while Compartments 71, 74, 67, and 55 are in Kuala Trong (Figure 1). We were unable to find another 30-year-old compartment in comparison to 67 due to rotation and harvesting practices.

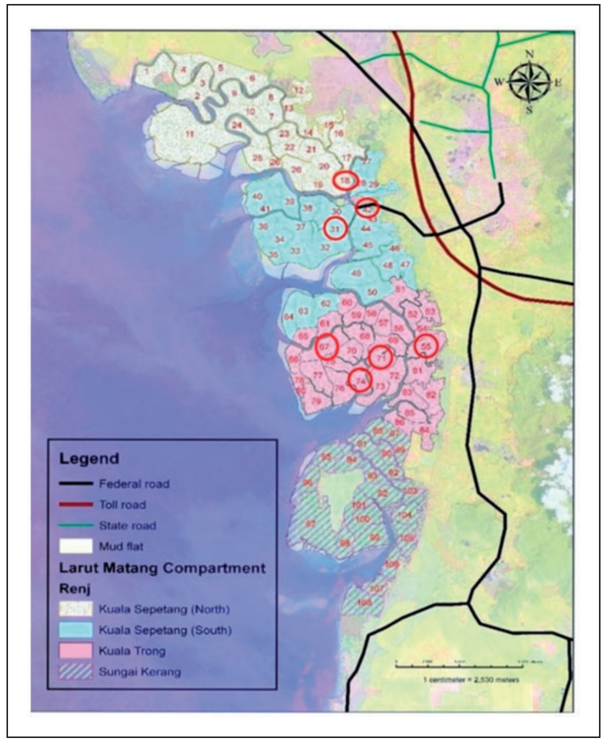

Figure 1. Encircled compartments with MMFR map.

Samples Collection

A total of 90 *Rhizophora apiculata* trees were chosen from six compartments (18, 31, 42, 71, 74, and 55), and mature leaf samples were collected. The research team was not able to get the leaf samples from Compartment 67 because the area was closed to carry out harvesting operation. Three plots (10 m $\times$ 10 m) were made in each compartment after the buffer zone and 15 samples from each compartment were collected randomly. Collected leaf samples were packed in zip plastic bag and placed in ice box to preserve it from contamination.

Trees Parameter Measurement

At transect from seaward to landward, eight plots (10 m $\times$ 10 m) were made in four compartments (18, 31, 71, and 74) and five plots (10 m $\times$ 10 m) were made at Compartment 67. The research team could only get measurement in five plots at compartment 67 because the following day the compartment was cleared fell and the team was unable to get an entry permit as the compartment was going under harvest. Tree parameters of diameter at breast height and height were measured with diameter tape and clinometer. No measurements were made VJR compartments because these compartments were untouched and unmanaged. Tree diameter at breast height and height were recorded at site.

Samples Preparation and Chemical Analysis

Elemental analysis. Samples were brought to the soil laboratory of Universiti Putra Malaysia (UPM). Leaves were washed with deionized water and dried until constant weight was achieved. Dried leaf samples were ground to fine and homogeneous powder. Sample digestion was performed as suggested by Zulkifli, Mohamat-Yusuff, Mukhtar, Ismail, and Miyazaki (2016) and Khan *et al.*, (2019). Samples were digested with concentrated nitric acid (HNO_3) and by heating on digestion block. After digestion, they were left to cool for 1 hr at room temperature. Cooled samples were filtered through Whatman filter paper in plastic bottles and diluted with deionized water. Elemental analysis Ca, Mg, Na, K, Cd, Cu, Fe, Mn, Pb, and Zn was performed in Faculty of Forestry UPM through Shimadzu Flame Atomic Absorption Spectrometer. For P%, detection blue method (Dick & Tabatabai, 1977) was chosen. Carbon, Nitrogen,Sulfur (CNS) percentage was analyzed through Trumac CNS analyzer in Faculty of Agriculture University Putra Malaysia.

Stable isotopes (δ13C, δ15N) analysis. The methodology proposed by Zulkifli, Mohamat-Yusuff, Ismail, and Miyazaki (2012) and Khan et al., (2019) was adopted for stable isotopes sample preparation. Ground leaves were fumed with 95% HCL for 12 hr to dissolve inorganic carbonates. Then samples were sent to Malaysia Nuclear Agency, Bangi for stable isotopes analysis. Stable carbon and nitrogen (13 C/12C, 15 N/14N) were examined through continuous flow isotopic ratio mass spectrometer environmental analyzer. Ratios of carbon and nitrogen are denoted with δ (δ13C, δ15N) in units' parts per thousand and can be measured by the following formula:

$$\delta X = [(Rsample/RStandard) - 1] \times 10^3$$

where X is 13 C and 15 N, and R is the corresponding ratio.

Statistical Analysis

SPSS version 25 was used for all statistical analysis and graphical representation. One-way analysis of variance and Tukey test were done to see the variation between mean and separate grouping. For correlation between 16 variables, Pearson correlation coefficient was computed.

Site differences were estimated through significant differences in mean values and the overview of differences in 16 variables of plants across the six sites. In addition, to analyze the variation of 16 variables in the leaf samples from six compartments, difference index (DI) was used which illustrated standardized anomaly versus overall average (Garten, Gentry, & Sharitz, 1977; Woodwell, Whittaker, & Houghton, 1975).

$$DI = (\text{site average} - \text{overall average}) / (\text{overall standard deviation})$$

According to Fry and Cormier (2011), productivity models were made through fractions that showed salt stress and nutrient abundancy. Fractions (f) for salt and nutrients were obtained through measured values related to low growth (LG) and high growth (HG).

$$f = (\text{sample} - LG)/(HG - LG)$$

LG and HG values indicate extreme end values of nutrients in each compartment.

Productivity models can be expressed as follows:

$$\text{Productivity} = \text{fsalt} \times \text{fnutrients}$$

As described earlier, two models were constructed. In first model, Na was used to show salt stress and N or P were used for nutrient indication. In second model, Na was replaced with δ13C due to similar properties of δ13C and Na. fNa and f δ13C were calculated using (Supplementary material) f data. fN and fP were calculated separately in both models. For productivity estimation, fN or fP can be chosen; however, Fry and Cormier (2011) used a lower f nutrient value for productivity estimation. Therefore, in this study, lower f nutrient value was chosen. Biomass of measured field data was calculated by using the formula given by Khoon and Eong (1995).

$$W_{ag}(\text{Total aboveground weight})\,Kg = 0.0135 \times G_{(130)}{}^{2.4243}$$

where $G_{(130)}$ is girth at 4.5 ft. height of the tree.

Results

Compartments 18 and 55 were distinctive to other compartments, especially relative enrichments at Compartments 18 and 55 were same, that is, for N and P were 1, 1 and 1.2, 1.2, respectively (Table 1). C/N and

Table 1. Representation of Elemental Composition for Mangrove Leaves.

Parameter	Units	Compartment 18 $n = 15$ Mean ± *SE*	Compartment 31 $n = 15$ Mean ± *SE*	Compartment 71 $n = 15$ Mean ± *SE*	Compartment 74 $n = 15$ Mean ± *SE*	Compartment 42 $n = 15$ Mean ± *SE*	Compartment 55 $n = 15$ Mean ± *SE*
δ15N	‰	$7.52^{a} \pm 1.400$	$8.67^{a} \pm 0.96$	$7.92^{a} \pm 2.035$	$3.57^{a} \pm 0.573$	$5.03^{a} \pm 1.056$	$7.07^{a} \pm 2.021$
δ13C	‰	$-27.90^{a} \pm 0.887$	$-29.34^{a} \pm 0.361$	$-30.54^{a} \pm 0.918$	$-30.37^{a} \pm .164$	$-31.43^{a} \pm 2.833$	$-29.67^{a} \pm 1.032$
Cd	mg/kg	$0.0046^{b} \pm 0.0008$	$0.016^{a} \pm 0.001$	$0.0107^{a} \pm 0.001$	$0.0098^{a,b} \pm 0.002$	$0.006^{a,b} \pm 0.001$	$0.0135^{a} \pm 0.002$
Cu	mg/kg	$0.107^{c} \pm 0.003$	$0.052^{a,b,c} \pm 0.007$	$0.067^{a,b} \pm 0.011$	$0.117^{b,c} \pm 0.006$	$0.085^{b,c} \pm 0.011$	$0.076^{a} \pm 0.009$
Fe	mg/kg	$2.156^{a} \pm 0.480$	$7.116^{a} \pm 2.160$	$2.59^{a} \pm 0.550$	$1.505^{a} \pm 0.341$	$3.75^{a} \pm 0.877$	$2.145^{a} \pm 0.74$
K	mg/kg	$29.40^{a} \pm 1.087$	$31.04^{a} \pm 0.764$	$29.41^{a} \pm 0.748$	$27.17^{a} \pm 1.89$	$30.70^{a} \pm 0.819$	$29.81^{a} \pm 1.53$
Mg	mg/kg	$1.78^{a} \pm 0.061$	$1.85^{a} \pm 0.036$	$1.84^{a} \pm 0.039$	$1.65^{a} \pm 0.079$	$1.82^{a} \pm 0.048$	$1.82^{a} \pm 0.04$
Mn	mg/kg	$2.03^{b} \pm 0.408$	$3.14^{a,b} \pm 0.543$	$3.57^{a,b} \pm 0.586$	$2.30^{b} \pm 0.351$	$5.36^{a} \pm 0.964$	$4.14^{a} \pm 0.41$
Pb	mg/kg	$0.046^{c} \pm 0.008$	$0.11^{a,b} \pm 0.017$	$0.143^{a} \pm 0.012$	$0.071^{b,c} \pm 0.013$	$0.066^{b,c} \pm 0.016$	$0.099^{b,c} \pm 0.014$
Zn	mg/kg	$0.428^{b} \pm 0.059$	$0.757^{a} \pm 0.076$	$0.536^{a,b} \pm 0.075$	$0.382^{b} \pm 0.058$	$0.573^{a,b} \pm 0.111$	$0.445^{b} \pm 0.046$
Na	mg/kg	$4,618.20^{a,b} \pm 177.322$	$4,806.66^{a} \pm 219.35$	$3,881.06^{b} \pm 186.65$	$4,414.06^{a,b} \pm 253.144$	$4,520.06^{a,b} \pm 265.23$	$4,946.80^{a} \pm 179.56$
Ca	mg/kg	$11,237.73^{a,b} \pm 144.288$	$10,788.63^{b} \pm 125.84$	$10,996.73^{a,b} \pm 170.024$	$10,808.86^{a,b} \pm 225.49$	$11,378.40^{a} \pm 91.252$	$11,362.26^{a,b} \pm 183.46$
C	%	$41.74^{a} \pm 0.706$	$39.096^{a,b} \pm 0.55$	$34.25^{b} \pm 2.18$	$38.80^{b} \pm 0.199$	$39.98^{b} \pm 0.30$	$39.007^{b} \pm 0.203$
N	%	$0.970^{a} \pm 0.098$	$12.01^{a} \pm 10.927$	$1.67^{a} \pm 0.126$	$1.21^{a} \pm 0.087$	$1.55^{a} \pm 0.131$	$1.26^{a} \pm 0.174$
P	%	$0.222^{b} \pm 0.012$	$0.276^{a} \pm 0.018$	$0.246^{a} \pm 0.020$	$0.328^{a} \pm 0.011$	$0.290^{a} \pm 0.012$	$0.283^{a,b} \pm 0.027$
S	%	$0.287^{b} \pm 0.010$	$0.367^{a,b} \pm 0.007$	$0.419^{a,b} \pm 0.016$	$0.357^{a} \pm 0.024$	$0.402^{a} \pm 0.016$	$0.344^{a,b} \pm 0.027$
C/N		43	3.2	21	32	26	31
C/P		188	141	139	118	137	137
N/P		4	44	7	4	5	4.5
Relative N		1	12.3	1.7	1.2	1.5	1.2
Relative P		1	1.2	1.1	1.4	1.3	1.2
Relative S		1	1.2	1.4	1.2	1.4	1.1
Relative Mg		1.0	1.1	1.1	1	1.1	1.1
Relative K		1.0	1.1	1.0	1	1.1	1.0
Relative Na		1.1	1.2	1	1.1	1.1	1.2
Relative Ca		1.0	1	1.0	1	1.0	1.0
Relative Fe		1.4	4.7	1.7	1	2.4	1.4

Note. Relative enrichment is given as a ratio of the listed average site values = (measured site value/lowest site value). Superscript letters in each row indicate significance groupings so that averages sharing the same superscript are similar and not significantly different ($p > .05$ and averages with different superscripts in each row are significantly different ($p < .05$). *SE* = standard error.

C/P ratios of Compartment 18 were higher than all the compartments with the values of 43 and 188, respectively. C/N and C/P ratios of Compartment 55 were intermediate in comparison to other compartments with the values of 31 and 137, respectively. Several parameters showed high or low values in Compartment 18. For instance, δ13C, Cd, Cu, Mn, Pb, C, S, and P showed high values in Compartment 18 (Figure 3). These eight variables were intercorrelated (Table 2) and anticipated for growth response or productivity. In Compartment 55, only Cd, Na, and Ca showed high values (Figure 3) and other variables were found intermediate. Further Ca and Na showed strong correlation in Compartment 55.

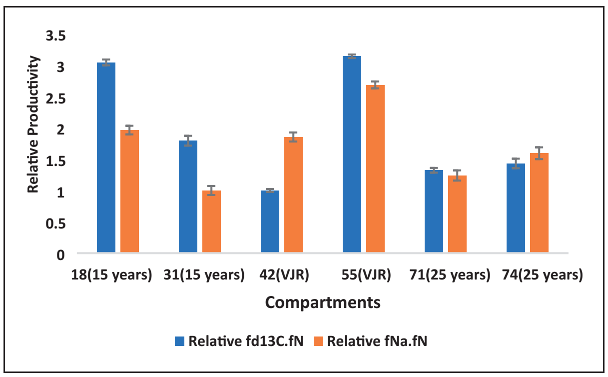

Figure 2. Modeled relative leaf productivities expressed for six compartments (18, 31, 42, 55, 71, and 74). Relative fδ13C.fN leaf productivities were expressed versus background values of Compartment 42, and relative fNa.fN were expressed versus background values of Compartment 31. VJR = virgin jungle reserve.

All compartments showed higher productivity (Figure 2) because predicted productivity estimation for these models started from 0 to 1. In this case, all the compartments showed higher values than 1. In relative compartment comparison, Compartments 18 and 55 showed higher productivity values; 3.04–3.14 in isotopic model, and 1.96–2.68 in sodium model, respectively. Comparison of productivity within same age compartments gave the following results: Compartment 18 had higher productivity compared with Compartment 31 (for 15-year-old site), Compartment 74 had higher than Compartment 71 (25-year-old site), and Compartment 55 higher than Compartment 42 (within VJR; Figure 2). Compartment 31 was distinct in terms of N that showed higher mean value of 12.01 compared with other compartments (Table 1). But for *p* values, Compartment 55 and Compartment 18 showed significant difference in mean values (0.222–0.283), respectively, in contrast with other compartments. In conjunction with N and P, other variables showed extreme high or low values in all the compartments (Figure 3). In correlation analysis, N showed no correlation with other elements, while P correlated only with Cu and Mg (Table 2).

Besides productivity models, field measurements were also carried out in five managed compartments (18, 31, 71, 74, and 67). AGB was calculated by the abovementioned formula. Compartment biomass range remained between 168 t ha^{-1} to 283 t ha^{-1} (Table 3). In case of biomass in same age compartments, Compartment 18 had higher compared with Compartment 31 (15-year-old site), and Compartment 74 had higher compared with Compartment 71 (for 25-year-old site; Figure 4). Biomass of Compartment 67 was in the range of the biomass in the two 25-year-old compartments (Table 3).

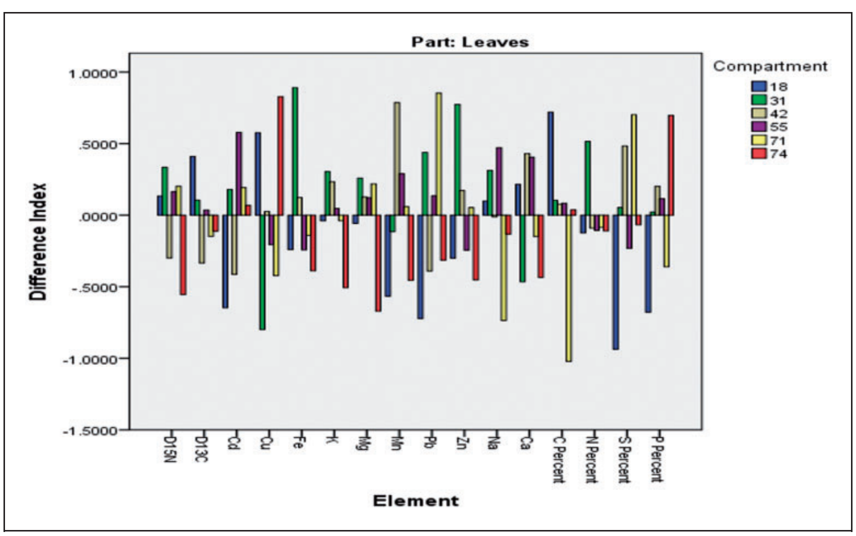

Figure 3. Average anomalies for leaf chemistry at the six compartments.

Table 2. Pearson Correlation for 90 Leaf Samples.

	δ15N	δ13C	Cd	Cu	Fe	K	Mg	Mn	Pb	Zn	Na	Ca	C%	N%	S%	P%
δ15N	1															
δ13C	.347a	1														
Cd	−.210b	−.245b	1													
Cu	−.261b	.158	−.032	1												
Fe	.164	−.078	−.057	−.299a	1											
K	−.052	−.016	−.036	−.267b	.214b	1										
Mg	.065	−.145	.099	−.543a	.285a	.684a	1									
Mn	−.101	.041	.095	.117	.099	.248b	.136	1								
Pb	.021	−.207	.522a	−.257b	.349a	.103	.326a	.351a	1							
Zn	.029	.223b	−.097	−.312a	.336a	.522a	.530a	.207	.105	1						
Na	.060	.153	.160	.041	.030	.015	−.087	−.044	−.053	−.064	1					
Ca	.107	.196	.177	.121	−.210b	−.162	−.219b	.004	−.234b	−.186	.281a	1				
C%	.025	.117	.013	.330a	−.029	.061	−.072	.113	−.141	.036	.063	.010	1			
N%	.035	−.011	.069	−.168	.070	.093	.055	.089	.030	.021	.115	.042	.010	1		
S%	−.292a	−.290a	.123	−.144	−.038	−.024	−.069	.224b	.238b	.107	.001	−.104	−.190	.135	1	
P%	−.135	−.045	.006	.210b	−.069	−.121	−.229b	.162	−.190	−.122	−.027	.180	.072	.008	−.025	1

[a]Correlation is significant at the .01 level (two-tailed).
[b]Correlation is significant at the .05 level (two-tailed). Sample type = leaves.

Table 3. Tree Parameters and Biomass Representation.

Compartment no.	Age (years)	Total plots	Stem diameter (cm) DBH	Mean height (m)	Density (ha^{-1})	Biomass (t ha^{-1})
18	15	8	5–15	12.9	2,075	235
31	15	8	6–15	13.1	1,901	168
71	25	8	7–35	14	1,287	241
74	25	8	6–36	14.2	1,175	283
67	30	5	6–35.3	13.9	1,690	266

Note. DBH = diameter at breast height.

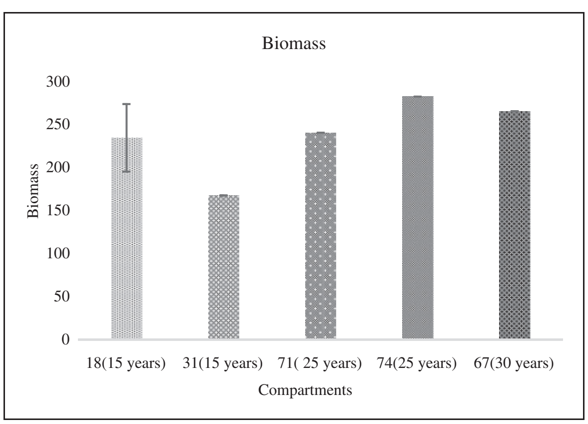

Figure 4. Calculated biomass for five compartments (18, 31, 71, 74, and 67).

Discussion

Productivity

Productivity can be defined as the *rate of generation of biomass in an ecosystem*. It is usually expressed as mass per unit surface. Two approaches were used to find out the productivity. In both leaf productivity models, the difference was of Na and δ13 C, as Na was replaced by δ13 C. As discussed earlier, for growth-limiting nutrients N and P were used in both models. f values were obtained by the calculation of lower value in the sample (LG) and the highest value (HG). Models results showed no similarity due to difference in δ13 C and Na values. However, based on Figure 2, a similar pattern was observed. Fry and Cormier's (2011) study showed similar results in models due to approximately same values of δ13 C and Na. But in the present study, these models were used and compared against AGB trend.

Five managed compartments were used for biomass calculations (Table 3). VJR compartments were not considered for biomass estimation due to the presence of heterogeneous species and those areas were unmanaged for the last 80 years. In short, the main concern of this study was managed compartments to see any significant trend in biomass/productivity. The graphical trend of productivity models and calculated biomass showed similar pattern (Figures 2 and 4).

Calculated biomass showed differences in values even within same-aged compartments, for example, Total

Above Ground (TAG) biomass of Compartment 18 was higher than Compartment 31. On the other hand, it was observed that the differences in TAG biomass were not considerably higher in 30-year-old sites as compared with 15-year-old sites (Table 3). The rotation period of MMFR plantation is 30 years. According to Khoon and Eong (1995), *Rhizophora apiculata* demonstrates no prominent enhancement in biomass after the age of 23 years. If the noticeable biomass is not achieved in 30-year-old site, then it is suggested that management should implement 25-year rotation period instead of 30 years (Khoon and Eong, 1995). However, due to some administrative short comings of Perak forestry department and contractors, it is difficult to change the 30-year rotation period (Goessens et al., 2014). In other words, it can be said that the biomass is sustained from 15-year aged plantation to 30-year aged plantation. Based on this idea, MMFR can be referred as sustainable and productive forest. To see the biomass trend in different age stands, a study conducted by Goessens et al. (2014) at MMFR showed biomass values of 216 t ha^{-1}, 217 t ha^{-1}, and 372 t ha^{-1} for 15-year, 20-year, and 30-year-old sites, respectively. Goessens et al.'s (2014) study contradicts present research in which after 15 years' time, the biomass of *Rhizophora apiculata* increased more than 150 t ha^{-1}. Second following Goessens et al.'s (2014) study about biomass increment from 20-year-old to 30-year-old plantation, it is still not possible for *Rhizophora apiculata* species to show a considerable biomass increment after the age of 23 years (Khoon and Eong, 1995). Another 30-year compartment comparison study was conducted for AGB and carbon stock estimation by Forestry Department Peninsular Malaysia at Matang (Hazandy, Ahmad, Zaiton, Tuan, & Mohammad, 2015). Compartments 37 and 69 (30-year-old) were selected. By using three allometric models in both compartments three different biomass values were calculated; 277 t ha^{-1}, 279 t ha^{-1}, and 267 t ha^{-1} biomass results were calculated in Compartment 37, and 318 t ha^{-1}, 276 t ha^{-1} and 334 t ha^{-1} biomass results were calculated in Compartment 69. Present research results for 30-year aged plantation were quite similar to Hazandy et al.'s (2015) third model result in Compartment 37 and second model result in Compartment 69.

Same age compartments showed differences in densities (Table 4). Densities can also be disturbed by late thinning. Early thinning concept at the age of 7,13 and 18 years was given by Khoon and Eong (1995) and Fontalvo- Herazo, Piou,Vogt, Saint-Paul, & Berger (2011) for more productivity instead of 15 and 20 years. As a result, differences in biomass and density are observed in the final harvesting of compartments. It was also suggested by Haron (1981) that thinning practice should be strictly controlled to prevent forest from degradation. In addition, present research revealed that the calculated biomass of 30-year aged plantation (266 t ha^{-1}) was in between 25-year aged plantations calculated biomass (Table 3). For comparison, it would have been better if the research team could have acquired biomass for another 30-year aged plantation.

Table 4 Density Comparison With Past Studies.

Compartments no (age)	Density (ha^{-1})	References
18 (15 years old age)	2,075	Present study
31 (15 years old age)	1,901	Present study
71 (25 years old age)	1,287	Present study
74 (25 years old age)	1,175	Present study
67 (30 years old age)	1,690	Present study
37 (30 years old age)	1,802	Hazandy et al. (2015)
69 (30 years old age)	1,084	Hazandy et al. (2015)
(15 years old age) Compt.	3,219	Fontalvo-Herazo et al. (2011)
(20 years old age) Compt.	1,649	Fontalvo-Herazo et al. (2011)
(15 years old age) Compt.	1,885	Goessens et al. (2014)
(20 years old age) Compt.	2,177	Goessens et al. (2014)
(30 years old age) Compt.	1,735	Goessens et al. (2014)

Note. Compt = compartment.

δ15N and N Indicators of N Loading

Nutrients loading can have a positive effect on productivity, as mangroves show more productivity at the polluted site. Role of N in productivity models is highly essential for productivity estimation. Compartments 18, 31, and 42 are located at Kuala Sepetang, which is considered as the most polluted area in MMFR (Harun, Nurhidayu, & Roslan, 2017). Compartment 42 is located near a populated area compared with 18 and 31 which are at a distant position. During sampling, it was observed that Compartment 18 was more polluted than others. Kuala Trong area compartments (71, 74, 55, and 67) were located far away from dense population. $\delta 15$ N values ranged from 3.57‰ to 8.67‰ and the highest value was observed in Compartment 31 and lowest value at Compartment 74 (Table 1). These $\delta 15$ N can be considered as moderate values because values from −2‰ to 3‰ range are an indication of background conditions (Muzuka & Shunula, 2006) and >10‰ are caused due to anthropogenic inputs (Hiam, Díaz, Essuman, Finlayson, & Sheth-Shah, 2015). Compartment 18 (15-year aged) was the most productive compartment, showing even higher productivity than the compartment with 25-year-old planation (Figure 2). In Compartment 18, moderate $\delta 15$ N value and less N values were observed, in contrast to Compartment 31 which was less productive in all the compartments and highest values of $\delta 15\,N$ and N were observed. It can be concluded that excessive nitrogen might be harmful by making a dead zone due to eutrophication (Rivera-monroy et al., 2004). Moreover, low $\delta 15\,N$ values could be due to fresh water runoff hindering the microbes to cause denitrification (Fry & Cormier, 2011). Therefore, N content and $\delta 15\,N$ both should be considered as tracers. C/N ratio is also used as a tracer to find out the N input. <18 C/N ratio depicts that area is enriched with nutrients and >37 shows less nutrients enrichment (Mckee, 1995). In this case, all compartments are in the moderate level of C/N ratio except Compartments 18 and 31 (Table 1). Compartment 31 is enriched with nutrients, and Compartment 18 is less enriched with nutrients. This can be accounted by the fact that Compartment 18 is under the effect of fresh water runoff.

Implications for Conservation

The study shows that productivity models using isotopes and nutrients are compatible with productivity estimations using biomass. Productivity models showed that there was a decrease in values for 25-year aged compartments compared with 15-year aged compartments. Based on this study, it can be said that productivity is declining from 15-year aged compartments to 25-year aged compartments. Future study on productivity in other forest types could be applied using similar approach.

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Supplemental Material

Supplemental material for this article is available online.

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