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Above and Belowground Carbon Acquisition of Mangrove *Kandelia obovata* Trees in Manko Wetland, Okinawa, Japan

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Abstract

Mangrove forests are crucial occupiers of the boundary between land and sea, being key ecosystems along many tropical and sub-tropical coastlines. Measuring carbon acquisition in trees is fundamental to understand the biomass, primary production and ecosystem function. We have estimated carbon acquisition of mangrove *Kandelia obovata* in Manko Wetland, Japan. A 1700 m² pure *K. obovata* closed canopy stand was marked. The stand was subjected to self-thinning. Height (H , m) and stem diameter at 10% height ($D_{0.1H}$, cm) of all the trees were measured. Aboveground individual mass w_T (kg) was estimated based on an allometric equation established from 25 trees data. Among 25 trees, all the roots including fine roots of five trees were collected and belowground mass was estimated by the summation. Tree density was 13588 ha⁻¹; aboveground carbon was calculated as 48.47 Mg C ha⁻¹; belowground carbon was calculated as 22.70 Mg C ha⁻¹ and the mean T/R ratio was found as 1.87 ± 0.01 (SE). Carbon acquisition potential of mangrove *K. obovata* is higher than many other terrestrial tree species.

Keywords: Carbon sequestration, Mangrove ecosystem, Manko wetland, Aboveground mass and belowground mass, T/R ration.

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I. INTRODUCTION

Trees, the main component of forest ecosystems, contain the largest stock or absolute quantity of the living forest biomass. Forests are important components of the terrestrial C cycle, and store large amounts of C in vegetation, detritus, and soil. Thus, C sequestration in sustainably managed forests can contribute to the drawdown of atmospheric CO₂ [1]. Mangrove forests inhabit the edge of tropical and subtropical seas. As cogently noted

by Alfred Russel Wallace during his equatorial travels, mangrove forests are crucial occupiers of the boundary between land and sea, being key ecosystems along many tropical and subtropical coastlines. They are true ecotones, being not just transitional in nature, having some elements of terrestrial and marine ecosystems, but having ecological characteristics all their own.

Mangroves cover a vast area of tropical and subtropical coasts. They play a major role in supporting coastal food webs and nutrient cycles in the adjacent coastal ecosystems [2, 3]. The high groundwater level in the soils of mangroves [4] brings about unique processes in primary production and biomass allocation, so that they are quite different from other forms of forests. Although mangroves are distributed only in the tropical and subtropical coasts, they play a significant contribution in carbon sequestration, as they show a high belowground production and a huge amount of organic matter is accumulated in their substrates [5–8]. Despite their ecological and economic values, they are disappearing at alarming rates throughout the world, mainly owing to unsustainable exploitation and anthropogenic activities. The significance of mangroves is highly

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acknowledged, though the reasons for it vary among regions and many processes are inadequately understood.

Quantification of biomass and net primary production is fundamental to the understanding of ecosystem functions. Reliable estimates of mangrove forest primary production enable predictions to be made for planning and management options. Moreover, precise estimation of their biomass is necessary for evaluating the carbon stocking pattern in the tropical and subtropical coasts. Although some studies have been conducted on mangrove biomass estimation [9–11], the overall productivity of mangroves remains little known. The aboveground biomass of mangrove forests are widely reported [12–19], however, the belowground biomass is less focused [7, 20]. Although quantitative net primary productions of terrestrial forests are widely reported [21–28], only a few studies have focused on mangroves [11, 12, 15, 17, 29, 30].

The present study area, Manko Wetland is a brackish tidal flat, covering an extensive area at low tide. The Manko tidal flats are an important transit point for shorebird whose migration route brings them along the Nansei Islands. The tidal flat is registered with the Ministry of Environment, Japan, as one of the 12 important shorebirds visiting sites nationwide. Owing to its importance, it was registered as Ramsar Convention site in 1999. However, recent observation claims that the number of flying birds in Manko Wetland is reducing gradually and the mangrove area is increasing every year (Ministry of Environment, Japan). Considering mangrove area extension as a factor to reduce the number of flying birds, the Ministry of Environment has taken a mangrove cutting program over 50 m x 50 m area, so that they can monitor the impact of mangrove area on bird. As a part of that inventory, the present research work attempts to quantify the carbon acquisition of a *Kandelia obovata* stand.

II. MATERIALS AND METHODS

A. Study site

This study was carried out at Manko Wetland (26°11' N and 127°40'E), in the southern part of Okinawa Island, Japan (Fig. 1). This wetland has been registered under the Ramsar Convention as an important stopover point and wintering area for migratory birds. On the basis of the data from 1997 to 2006 (Okinawa Astronomical Observatory), the warmth index

was $220.4 \pm 0.1^\circ\text{C}$ month, which is within the range of 180 to 240°C month of the subtropical region. The mean annual temperature was $23.4 \pm 0.1^\circ\text{C}$; the mean monthly minimum temperature of $17.1 \pm 0.3^\circ\text{C}$ and the mean monthly maximum temperature of $28.8 \pm 0.2^\circ\text{C}$ occurred in January and July, respectively. The mean monthly rainfall was over $100 \text{ mm month}^{-1}$ throughout the year and the mean annual rainfall was $2227 \pm 163 \text{ mm yr}^{-1}$.

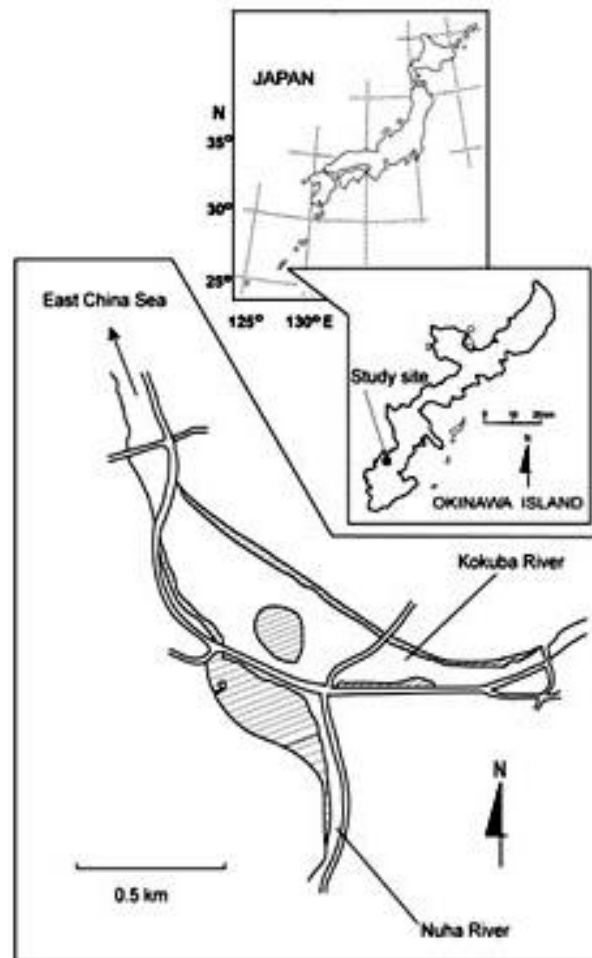


Fig. 1. Location map of the study area

B. Tree census

Within the selected area (2500 m^2) of the Ministry of Environment, 1700 m^2 pure *K. obovata* close canopy stand was marked. The stand was subjected to self-thinning. The area was divided into 68 uniform plots of $5 \text{ m} \times 5 \text{ m}$ each. A tree census was carried out in the 68 plots. Height (H , m) and diameter at 10% height ($D_{0.1H}$, cm) of all the trees were measured. The tree density, stand age, mean tree height and mean $D_{0.1H}$ were respectively 13588 ha^{-1} , 14yr, 4.18m and 6.13cm (Table 1).

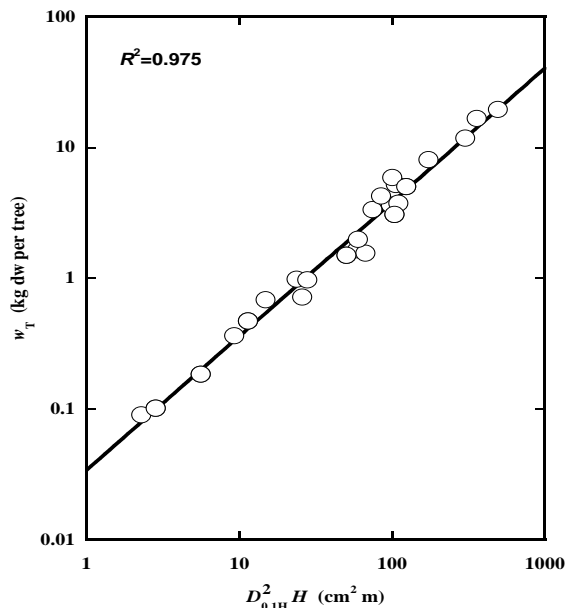
Table 1. General description of 68 plots (5 m x 5 m each and total 1700 m²) in the *K. obovata* stand.

Parameter	Magnitude
Stand age	13 yr
Tree density	13588 ha ⁻¹
Mean H	4.17 ± 0.05 (SE) m
Maximum H	6.92 m
Mean $D_{0.1H}$	5.83 ± 0.04 (SE) cm
Maximum $D_{0.1H}$	19.42 cm

C. Measurement of aboveground mass

Thirteen sample trees representing different size classes available in the whole Manko Wetland were harvested to measure the individual aboveground mass w_T (kg tree⁻¹). After the sample trees were felled, their H and $D_{0.1H}$ were measured, and then the leaves and branches were separated from the stem. The fresh weight was measured for the stem, branches and leaves. Samples of the stem, branches and leaves were taken for estimating the ratio of dry/fresh mass. All samples were dried in a ventilated oven at 85°C for 72 h and were desiccated at a room temperature, and then weighed. Finally w_T was calculated by summation. A data set of 12 trees from a previous paper [31] was added. As a result, data from 25 trees were used for the establishment of the allometric relationship. As shown in Fig. 2, the resultant allometric relationship was given in the form [32]:

$$w_T = 0.0341(D_{0.1H}^2 H)^{1.03} \dots \dots \dots (1)$$

Fig. 2. Allometric relationship of aboveground mass w_T to $D_{0.1H}^2 H$ of *Kandelia obovata* trees.

D. Measurement of belowground mass

Among 13 plants, harvested 5 plants were selected to measure the aboveground and belowground mass separately which were finally used to estimate belowground carbon acquisition following the relationship between aboveground and belowground mass. All the roots including fine roots were collected and washed carefully. Fresh weight was measured after all the root components (hard, soft and fine roots) were carefully cleaned following Komiyama et al. [33]. Samples from different types of root were taken to the laboratory, dried in a ventilated oven at 85°C for 72 h and were desiccated at a room temperature, and then weighed. Finally, belowground mass of individual trees were calculated.

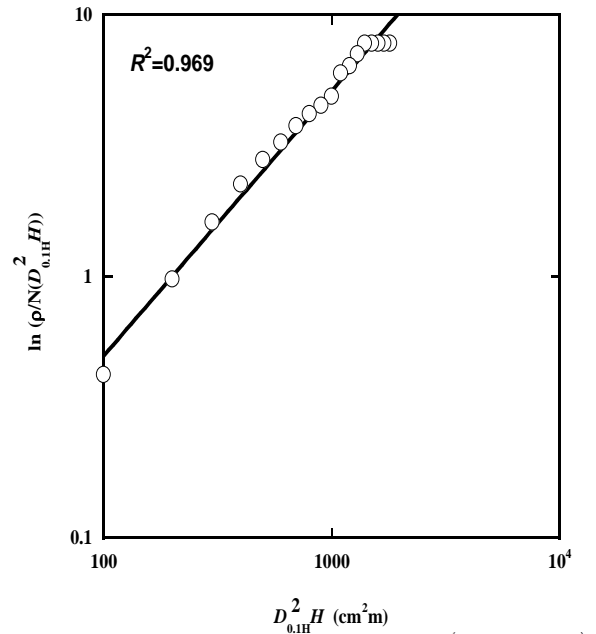
III. RESULTS

A. Frequency distribution of $D_{0.1H}^2 H$

The frequency density function ϕ of $D_{0.1H}^2 H$ for the *K. obovata* stand is assumed to be expressed by a Weibull density function:

$$\phi(D_{0.1H}^2 H) = \rho \cdot \frac{\alpha}{\lambda} \cdot \left(\frac{D_{0.1H}^2 H}{\lambda} \right)^{\alpha-1} \cdot e^{-\left(\frac{D_{0.1H}^2 H}{\lambda} \right)^\alpha} \quad (\alpha, \lambda) > 0 \quad \dots \dots (2)$$

here ρ is the stand density, and α and λ are constants. $D_{0.1H}^2 H$ yielded better allometric relationship than DBH. Hence $D_{0.1H}^2 H$ was used as an independent variable [31, 34, 35].

Fig.3. Linear relationship between $\ln\{\phi/N(D_{0.1H}^2 H)\}$ and $D_{0.1H}^2 H$ on log-log coordinates, given by Eq. (4).

The values of α and λ were obtained using the relationship between $D_{0.1H}^2 H$ and the tree density of a partial population $N(D_{0.1H}^2 H)$, which is defined as follows,

$$N(D_{0.1H}^2 H) = \int_{D_{0.1H}^2 H}^{D_{0.1H}^2 H_{(\max)}} \phi(D_{0.1H}^2 H) \cdot d(D_{0.1H}^2 H) \dots \dots \dots (3)$$

where $N(D_{0.1H}^2 H)$ means the number of trees from the maximum size of $D_{0.1H}^2 H_{(\max)}$ to a given size of $D_{0.1H}^2 H$.

Inserting Eq. (2) into Eq. (3) and assuming $D_{0.1H}^2 H_{(\max)}$ to be infinite, the integral is led to

$$\ln\left(\frac{\rho}{N(D_{0.1H}^2 H)}\right) = \ln\left(\frac{1}{\lambda}\right)^\alpha + \alpha \cdot \ln(D_{0.1H}^2 H) \dots \dots \dots (4)$$

As shown in Fig. 3, the relationship between $\ln\left\{\rho/N(D_{0.1H}^2 H)\right\}$ and $D_{0.1H}^2 H$ was linearly related on log-log coordinates. The slope and the intercept of the straight line correspond to α and $\ln(1/\lambda)^\alpha$, respectively. The estimated value of α and λ were 1.0124 and 199.71 $\text{cm}^2 \text{ m}$, respectively.

The frequency distribution of $D_{0.1H}^2 H$ for the *K. obovata* stand is shown in Fig. 4.

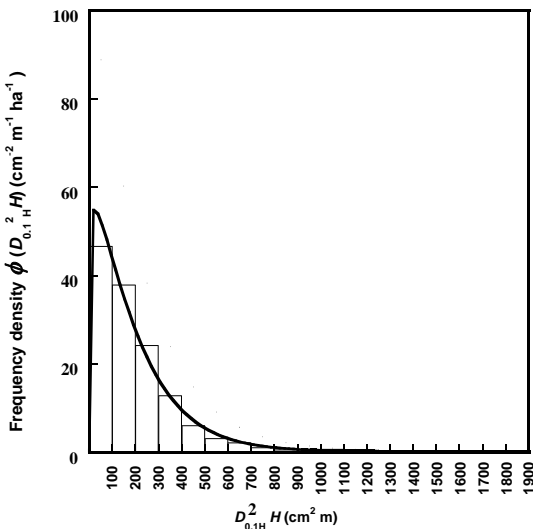


Fig. 4. Frequency density of $D_{0.1H}^2 H$ in the *Kandelia obovata* stand. The smooth curve represents an approximation given by Eq. (2).

B. Aboveground carbon estimation

The law of allometry applies to the relationship between the aboveground mass w_T (kg) and $D_{0.1H}^2 H$ ($\text{cm}^2 \text{ m}$). This relationship can be written in the allometric equation, namely,

$$w_T = g \cdot (D_{0.1H}^2 H)^h \dots \dots \dots (5)$$

where g and h are coefficients. From Eqn. (1) the corresponding values were $3.41 \times 10^{-2} \text{ kg} (\text{cm}^2 \text{ m})^{-h}$ and 1.03 respectively. Total amount of aboveground biomass y_T is expressed by the following integral,

$$y_T = \int_{D_{0.1H}^2 H_{(\min)}}^{D_{0.1H}^2 H_{(\max)}} w_T \cdot \phi(D_{0.1H}^2 H) \cdot d(D_{0.1H}^2 H) \dots \dots \dots (6)$$

Considering Eqns. (5) and (6), the result of the integral is given by the formula,

$$y_T = \rho \cdot g \cdot \lambda^h \cdot \Gamma\left(1 + \frac{h}{\alpha}\right) \dots \dots \dots (7)$$

where, $D_{0.1H}^2 H_{(\min)}$ and $D_{0.1H}^2 H_{(\max)}$ are assumed to be zero and infinite, respectively. Based on the Eq. (7), aboveground biomass was found as 109.28 Mg ha^{-1} (48.57 Mg C ha^{-1}).

C. Belowground carbon estimation

Based on 5 sample plants, the relationship between aboveground mass w_T and belowground mass w_R was well expressed through an allometry. As shown in Fig. 5, the resultant allometric relationship was given in the form:

$$w_R = 0.745(w_T)^{0.810} \dots \dots \dots (8)$$

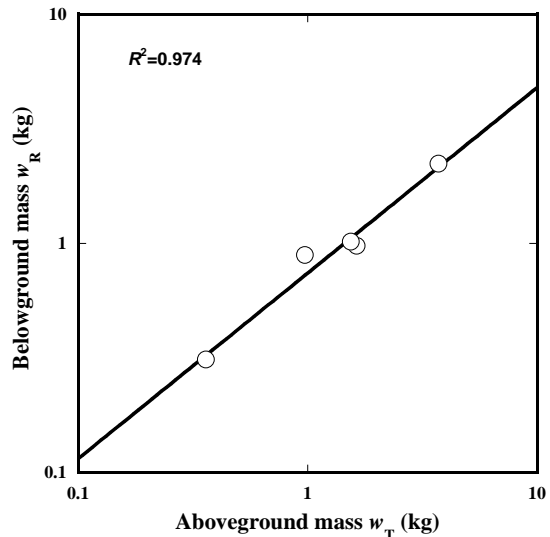


Fig. 5. Allometric relationship between aboveground individual mass and belowground individual mass.

Putting the Eq. (1) into Eq. (8), Eq. (8) can be rewritten in the form:

$$w_R = 0.0483(D_{0.1H}^2 H)^{0.834} \dots \dots \dots (9)$$

The law of allometry applies to the relationship between the belowground mass

w_R (kg) and $D_{0.1H}^2 H$ ($\text{cm}^2 \text{ m}$). This relationship can be written in the allometric equation, namely,

$$w_R = g_1 \cdot (D_{0.1H}^2 H)^{h_1} \dots \dots \dots (10)$$

where, g_1 and h_1 are coefficients. From Eq. (9) the corresponding values were $4.83 \times 10^{-2} \text{ kg}(\text{cm}^2 \text{ m})^{-h_1}$ and 0.834 respectively. Total amount of belowground biomass y_R is expressed by the following integral,

$$y_R = \int_{D_{0.1H}^2 H_{(\min)}}^{D_{0.1H}^2 H_{(\max)}} w_R \cdot \phi(D_{0.1H}^2 H) \cdot d(D_{0.1H}^2 H) \dots \dots (11)$$

Considering Eqns. (10) and (11), the result of the integral is given by the formula,

$$y_R = \rho \cdot g_1 \cdot \lambda^{h_1} \cdot \Gamma\left(1 + \frac{h_1}{\alpha}\right) \dots \dots \dots (12)$$

where $D_{0.1H}^2 H_{(\min)}$ and $D_{0.1H}^2 H_{(\max)}$ are assumed to be zero and infinite, respectively.

Based on the Eq. (12), belowground biomass was found as 51.08 Mg ha^{-1} ($22.70 \text{ Mg C ha}^{-1}$). Therefore, top and root ratio (T/R) was 1.87 ± 0.01 .

IV. DISCUSSION

DBH is commonly used as the basis of the Weibull frequency density distribution function [36, 37]. However, we used, $D_{0.1H}$ ($D_{0.1}$ stem diameter at a height of one-tenth of tree height, H tree height) for the *K. obovata* stand because it provides better allometric relationship than D (DBH) or $D^2 H$ [31, 34, 35]. Aboveground carbon of studied *K. obovata* stand was $48.57 \text{ Mg C ha}^{-1}$ which is equivalent to the aboveground biomass of $109.28 \text{ Mg ha}^{-1}$. This biomass is much lower than 281 Mg ha^{-1} in the mature *Rhizophora* forest [14], 357 Mg ha^{-1} in a mature *Sonneratia* forest [20] and 315 Mg ha^{-1} in a mature *A. germinas* [38], but closer to 94.8 Mg ha^{-1} in a secondary mangrove forest of *R. mucronata* and *B. gymnorhiza* [13] and 62.9 Mg ha^{-1} in a young *R. mangle* forest [39]. In a previous study Khan *et al.* [30] reported the aboveground biomass of a comparatively less mature/aged *K. obovata* stand was 80.5 Mg ha^{-1} . The difference between two study reports could be due to the age of the studied stand. Besides, the simple summation method and the Weibull distribution model showed closer values of the aboveground carbon estimation. The belowground carbon of the *K. obovata* stand was $22.70 \text{ Mg C ha}^{-1}$. It is equivalent to the belowground biomass of 51.08 Mg ha^{-1}

which quantity is much smaller than $106\text{--}173$ and $187\text{--}273 \text{ Mg ha}^{-1}$, respectively in *Bruguiera* and *Rhizophora* mature forests [20] and 87.5 Mg ha^{-1} in the *C. tagal* secondary forest [7], but higher than 32.4 Mg ha^{-1} in the mature *Sonneratia* forest [20]. In case of belowground carbon the simple summation method and the Weibull distribution model showed closer values of the belowground carbon estimation.

Generally mangroves show relatively high amount of root biomass than other forms of forests [5, 6, 7]. The T/R ratio in some temperate forests ranged from 2.68 to 3.70 [40, 41, 42]. In the tropical inland forests, the T/R ratio ranged from 5.10 to 10.7 [43, 44]. It is noteworthy that the large biomass was allocated to the underground roots in the pioneer mangrove *K. obovata* has revealed by the low T/R ratio. Mangroves are usually coping with the stresses of high water tables, salty soil and less mechanical support due to soft muddy substrate. Therefore, a large allocation of the net production into roots may be necessary. The top/root (T/R) ratio is a standard to judge the carbon-allocation pattern to the underground part of a forest. The T/R ratio for the *K. obovata* stand was 1.87, which is fairly similar to 1.72 for an *A. marina* [45] and a bit higher from 1.05 in the *C. tagal* forest [7]. *Rhizophora* forest [14] show a little higher (2.27) T/R ratio.

V. CONCLUSION

The result implies that Weibull frequency density distribution function is applicable for estimation carbon acquisition and stand biomass indirectly. Mangroves show relatively high amount of root biomass than other forms of forests which means higher carbon is accumulated in the belowground root region for mechanical support on soft mud substrate. Mangroves have higher potentials to mitigate the climate change scenarios through carbon acquisition compared to other contrasting ecosystems. Hence, knowledge regarding the basic process of carbon dynamics in mangrove forest, the carbon acquisition potentials of different aged stands and in different other parts of the mangrove distribution would be of significant importance in planning and management options to mitigate the threat of global warming and climate change.

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