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Tradeoffs between reducing flood risks and storing carbon stocks in mangroves

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A B S T R A C T

Mangrove habitats are important carbon(C) reserve sites. However, the overgrowth or overexpansion of mangroves may increase the risk of flooding, thus affecting human wellbeing. To decrease the flood risks, partial mangrove removal has been proposed as a managerial action, which would decrease the C stocks. Using the Danshuei River as a case study, the objective of this study was to determine the optimal removal area to allow the mangroves to meet the demands of reducing the loss of mangrove C stocks and adequately controlling the flood risks. Our results show that the ratios of the effective reduction in flood level (benefit) and the loss of mangrove C stocks (cost) were only higher under the condition of the removal of aboveground structures of mangrove trees than the ratios under the condition of the removal of both above- and belowground structures. The highest ratio of the effective reduction in flood level and the loss of mangrove C stocks occurred under the condition of removal of 20% of aboveground structures of mangrove trees, indicating the optimal removal area for mangrove management in the Danshuei River. This study provides a case study exhibiting the tradeoffs between ecosystem services in mangrove management.

1. Introduction

Natural carbon (C) uptake and storage by coastal vegetation offers a sustainable, low-risk, and potentially significant contribution toward managing the C problem, known as “blue carbon” or “missing carbon sinks” (Irving et al., 2011; Nellemann et al., 2009; Schindler, 1999). Mangroves are a major vegetation type along undisturbed coastlines in the tropics and subtropics. They are one of the most important C-rich ecosystems on the planet. Mangroves have larger per-hectare C stocks than marshes (Adame et al., 2013) and boreal, temperate, and other tropical forests (Donato et al., 2011; Kauffman et al., 2011). The exceptionally high C storage in mangrove forests can be attributed in part to the relatively high belowground: aboveground ratio of plants and organic-rich soils that are often more than 3 m in depth (Donato et al., 2011).

Mangroves are important not only because of their value in C sequestration and storage but also because they offer numerous ecosystem services, such as supporting coastal fisheries (Barbier, 2000; Diele et al., 2005) and providing shelter and food for motile fauna such as birds, prawns, crabs and fishes (Mumby et al., 2004). Furthermore, mangroves can offer protection from erosion and devastation caused by tsunami-induced waves (Kathiresan and Rajendran, 2005; Walters et al., 2008) and rising sea level (Gilman et al., 2008). However, mangrove overgrowth or area extension may shift the benthic community and reduce the biodiversity (Huang et al., 2012).

Mangrove trees can be aggressive colonizers in estuaries and coasts (Schwarz, 2003). The roughness of mangrove trees is much greater than mudflats and marshes (Lee and Shih, 2004). An increased roughness coefficient of the riverbed reduces flow velocity and elevates water surface levels (Chow, 1973). Densely populated mangrove trees with increasingly complicated stand structure decrease the conveyance area and flow velocity (Lee and Shih, 2004) and thus raise water surface levels. Reduced flow velocity also induces sediment deposition and causes the further accretion of mangrove vegetation (Li and Shen, 1973). The

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consequences of water surface elevations would pose a flood threat to the local residents' lives and their settlements along the river.

In northern Taiwan, improper planting since 1959 has resulted in mangrove overexpansion along the Danshuei River (Shih et al., 2011). Such uncontrolled expansion of mangroves results in a series of alterations to both the hydrological regime and biotic community, such as increasing flood risks, replacing shorebirds with tree birds, diminishing benthic diatom production, changing the dominance of benthic communities from polychaetes and amphipods to crabs (Lee and Chu, 1999; Lee and Shih, 2004; Huang et al., 2012), which led to the local extinction of the sedge *Cyperus malaccensis* (Wester and Lee, 1992; Lee et al., 2002), and confining the distribution of the Taiwan endemic fiddler crab *Uca formosensis* (authors' personal observations). To decrease flood risks and restore biodiversity, partial mangrove removal has been proposed as a managerial action. However, we reasoned that partial removal would thus reduce the C stocks of mangroves due to the loss of mangrove trees. Using the Danshuei River as a case study, the objective of this study was to optimize the removal area to allow the mangroves to meet the demands of small losses in mangrove C stocks and effectively control flood risks.

2. Methods

2.1. Study area

The study area is located at the Guandu wetland (25°07′10″ N; 121°27′43″ E) close to Taipei City in the estuary of the Danshuei River, northern Taiwan (Fig. 1). The Danshuei River consists of three main tributaries: the Dahan Creek, the Hsindian Creek and the Keelung River. The mainstream is approximately 158 km long with a watershed covering 2726 km^2. In the estuary, the M2 tide is the primary tidal constituent (Liu et al., 2007), with a mean tidal range of 2.17 m and up to 3 m during spring tides. The salinity profile of the estuary was characterized as homogeneous because the difference in the mean salinity concentration between the top and bottom layer was less than 15%. The boundaries of the tidal region, at which the elevation of the riverbed approaches the mean annual water level, were derived from Shih et al. (2011).

In the Danshuei Estuary, the mangroves are mainly distributed on the convex bank in meandering bends (Fig. 1). The four major mangrove-vegetated wetlands are the Wazwei, Zhuwei, Guandu, and Shezi wetlands. With the exception of the Shezi wetland, all the wetlands have been designated as reserves under the Taiwan Culture Heritage Reservation Act (http://conservation.forest.gov.tw/lp.asp?ctNode=725&CtUnit=601&BaseDSD=7&mp=11). They are all composed of the species *Kandelia obovata*. The earliest record of the mangrove species *K. obovata* in the Guandu wetland can be dated to 1978 (Lin and Chiou, 1989). These habitats possess the largest population of *K. obovata* in the Northern Hemisphere (Hsu, 2002) and represent the species' northern most geographical distribution (Lee and Yeh, 2009).

The distribution area of mangroves in the Guandu wetland is 14 ha. The side of the wetlands near the Keelung River is subjected to a semidiurnal tidal regime with a tidal amplitude of approximately 1–2 m. The water temperature of the river at Guandu ranged from 18 °C in February to 28 °C in July. The salinity of the overlying waters ranged from 7 to 12 at low tide and may reach 25 at high tide (Lin et al., 2003). Yang et al. (2013) found that the inundations of the highest and the lowest elevations for the mangrove habitat increased, whereas the salinity decreased. The hydro-geomorphology of the Danshuei Estuary demonstrated that a critical combination of hydraulic- and geomorphic-driving forces affects the distribution of the mangrove *K. obovata*. They concluded that spontaneous seedlings of *K. obovata* can occur when the stressors are removed and suitable hydrological conditions reappear in the Danshuei Estuary.

2.2. Evaluation of flood inundation risks

The flow diagram for the methodology to determine the optimal removal area of mangroves is shown in Fig. 2. Increasing mangrove

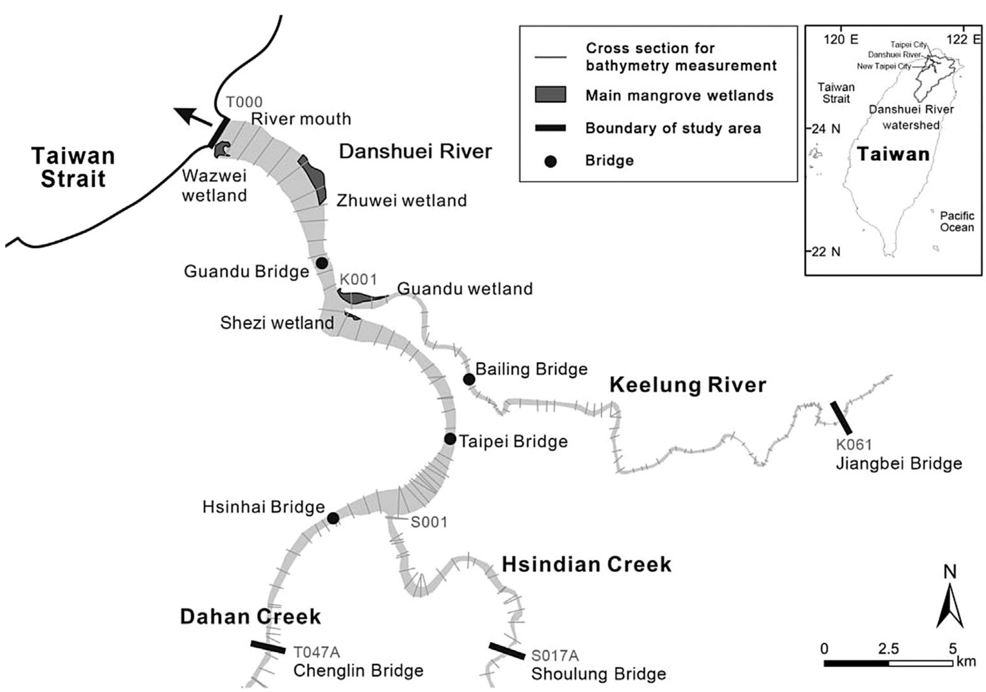

Fig. 1. Map of the study area in the estuary of Danshuei River. The distance from the estuary to junctions at the Keelung River and the Hsindian River is 8.6 km and 21.1 km, respectively. The four major mangrove-vegetated wetlands within the study area are the Wazwei, Zhuwei, Guandu, and Shezi wetlands.

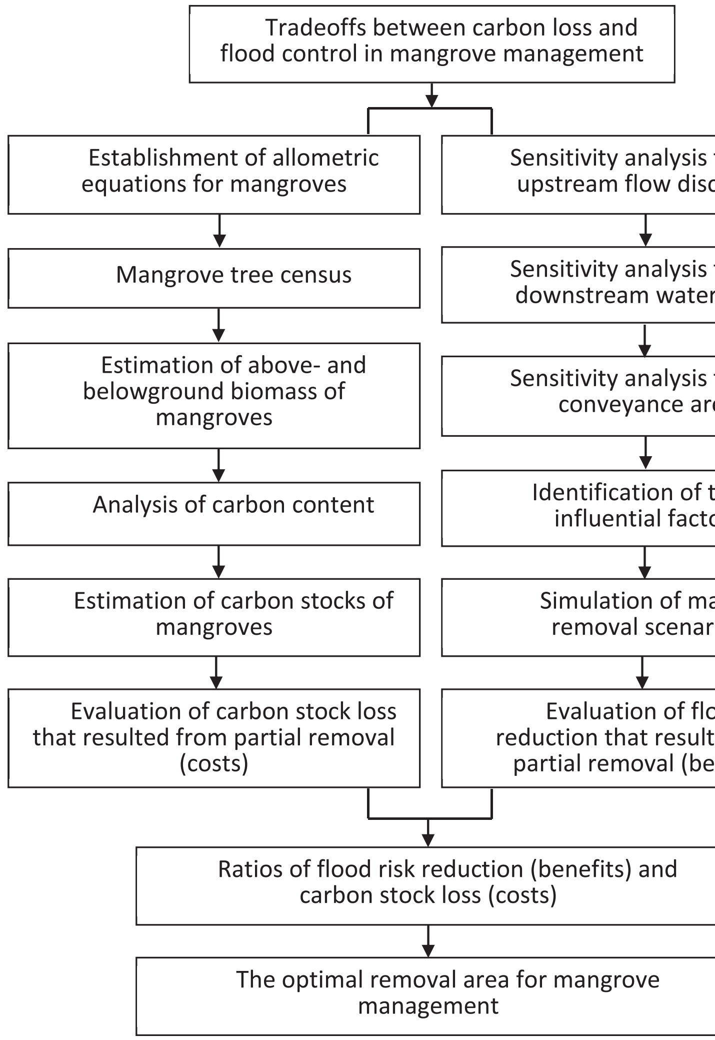

Fig. 2. The flow diagram for the methodology to determine the optimal removal area to allow the mangroves to meet the demands of reducing carbon stock loss and controlling flood risks.

coverage may decrease the water conveyance area and thus increase the flood risk. A well-defined numerical model, the Hydrologic Engineering Centers River Analysis System (HEC-RAS), was used to simulate the hydraulic characteristics, including the flow velocity and water depth. HEC-RAS is capable of performing one-dimensional water surface profile calculations for steady and gradually varied flows. In addition, subcritical, supercritical, and mixed flow regime water surface profiles can be calculated (Brunner, 2010). Water surface profiles and water velocity magnitude were computed from one cross section to the next by solving the Energy equation with an iterative procedure called the standard step method (U.S. Army Corps of Engineers, (2010a)).

The downstream and upstream boundaries of the river network simulation were as follows: the estuary of the Danshuei River (T000), the Jiangbei Bridge of the Keelung River (K061), the Chenglin Bridge of the Dahan Creek (T047A) and the Shoulung Bridge of the Hsindian Creek (S017A). The flow discharges of tributaries were taken into account as lateral inflows.

We calculated the conveyance width reduction by incorporating data from mangrove tree density surveys using aerial photo mapping (Fig. 3a). The mangrove tree density was used to calculate the porosity and to observe the changes in water conveyance area. The "obstruction" function in the HEC-RAS model was applied to simulate the effect of declining water conveyance area occupied by mangrove trees. This option allows the user to define areas of the cross section that will be permanently blocked out. Obstructions decrease flow conveyance area and add wetted perimeter when the water comes in contact with the obstruction (U.S. Army Corps of Engineers, (2010b)).

The Energy equation is written as Eq. (1). The energy head loss between two cross sections is comprised of friction losses and contraction or expansion losses as shown in Eq. (2).

$$Z_2 + Y_2 + \frac{\alpha_2 V_2^2}{2g} = Z_1 + Y_1 + \frac{\alpha_1 V_1^2}{2g} + h_e \tag{1}$$

where: Z_1, Z_2 = elevation of the main channel inverts.

Y_1, Y_2 = depth of water at cross sections.
V_1, V_2 = average velocities (total discharge/total flow area).
α_1, α_2 = velocity weighting coefficients.
g = gravitational acceleration.
h_e = energy head loss.

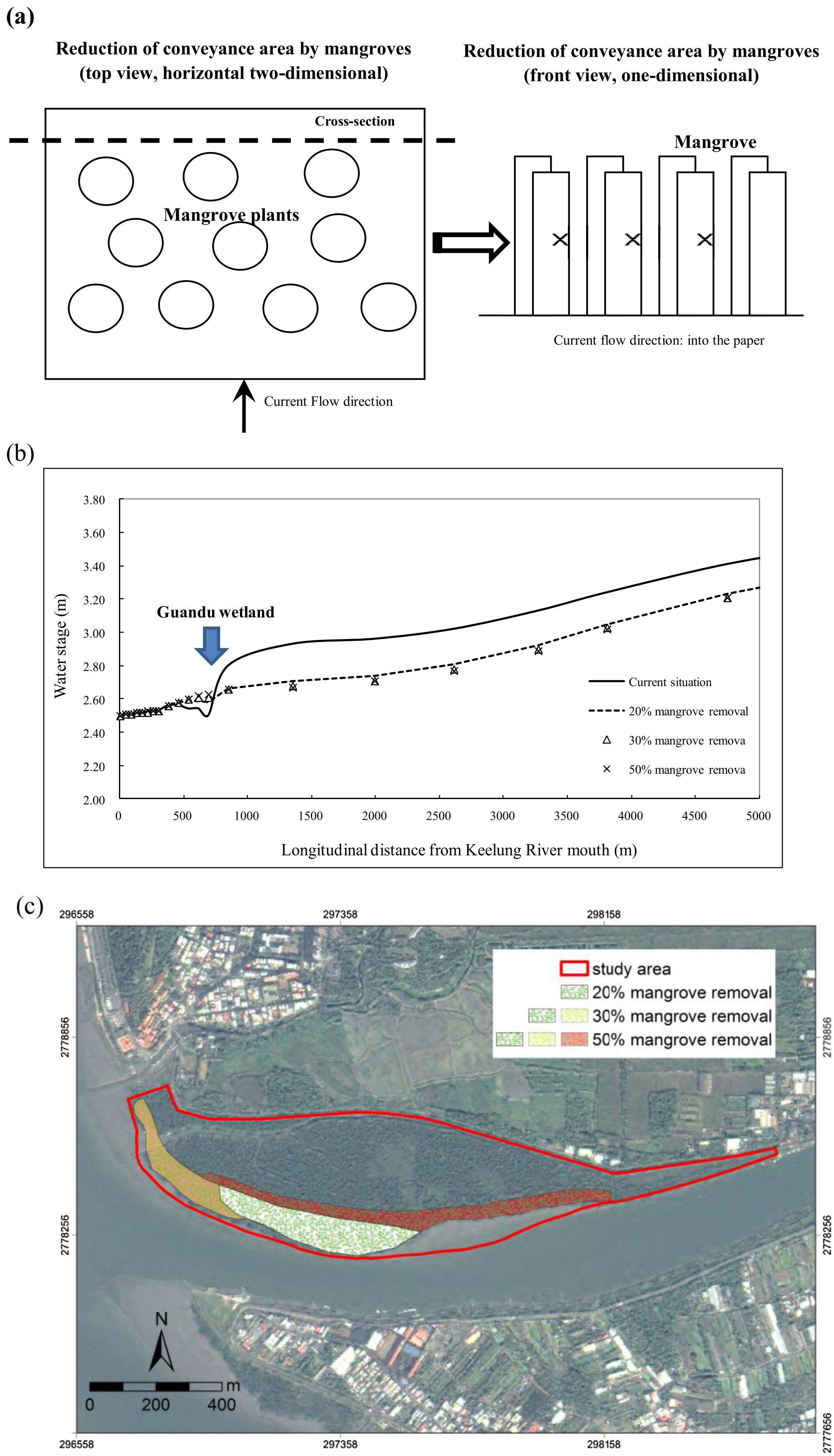

Fig. 3. (a) A schematic diagram shows the reduction of conveyance area by mangroves growth and the shadow effects associated with the obstruction concept applied in Hydrologic Engineering Centers River Analysis System (HEC-RAS). (b) Longitudinal variations of water stage before and after partial removal of mangrove trees in the Guandu wetland. (c) The area and location of three mangrove removal cases.

$$h_e = L\bar{S}_f + C\left|\frac{\alpha_2 V_2^2}{2g} - \frac{\alpha_1 V_1^2}{2g}\right| \quad (2)$$

where: L = discharge weighted reach length.

$\bar{S}_f$ = representative friction slope between two cross sections.
C = expansion or contraction loss coefficient.

The input data of HEC-RAS includes the networking river bathymetry (river connectivity, cross-sectional geometry, reach lengths) and hydraulic data (upstream flow discharge and downstream water stage). The HEC-RAS model adopted the cross-sectional bathymetry of the Danshuei River system as the topography data. The study used the investigation of each cross section bathymetry in the year 2012 conducted by the Tenth River Management Office, Water Resources Agency. The parameters of HEC-RAS were set following those of our previous study in the same area (Shih et al., 2014). Sensitivity analysis was conducted to identify the most influential factors that affected flood levels, such as upstream flow discharge, downstream water stage, and conveyance area (Table 1).

2.3. Estimation of mangrove carbon stocks

2.3.1. Establishment of allometric equations

Mangrove allometry is site- and species-specific (Komiyama et al., 2008). In order to apply allometric equations to estimate the biomass of mangrove trees in the Guandu wetland, the above- and belowground structures of 7 sample trees of *K. obovata* with diameters ranging from 1 to 11 cm (representing various size classes) were harvested from the Shezi wetland (Fig. 1) in April 2013 by covering the trees with screens to prevent the loss of leaves and branches when handling. The Shezi wetland is located on the opposite side of the Keelung River across the Guandu wetland, and the growth condition of mangroves is similar to that in the Guandu wetland. The height (H, m) and diameter at 10% height from the ground ($D_{0.1}$, cm) of all the trees were measured. In the laboratory, the soil on the belowground structures was carefully washed and removed. The stems were cut into pieces of 10–15 cm. All the leaves, branches, roots, fruits, flowers, and stem pieces were sorted and weighed. Next, these materials were weighed again after drying in an oven at 75 °C for at least 4 days. The observed dry weights of trees were used to establish the allometric relationship following the approach of Khan et al. (2005) to estimate the biomass of *K. obovata* in the Guandu wetland.

Table 1
Scenarios of the sensitivity analysis for flood stage simulation.

	Note
Upstream flow discharge (m^3/sec)	
1200	2-year return period flood
1780	5-year return period flood
2120	10-year return period flood
2400	20-year return period flood
3200	200-year return period flood
Downstream water stage (m)	
3.45	200-year return period water stage × 150%
2.87	200-year return period water stage × 125%
2.30	200-year return period water stage
1.72	200-year return period water stage × 75%
1.15	200-year return period water stage × 50%
Conveyance width occupied by mangrove trees (m)	
90	Current situation
72	Minus 20% mangrove coverage
63	Minus 30% mangrove coverage
45	Minus 50% mangrove coverage

2.3.2. Tree census and carbon content

In the Guandu wetland, 3 quadrats (measuring 5 × 5 m) separated from each other by 15 m were selected in the proposed removal area of the mangrove forest. In total, 49 trees within the quadrats were measured to determine the H and $D_{0.1}$. The measurements were conducted in October 2011, June 2012, and November 2012. The measured H and $D_{0.1}$ were used as the inputs for the derived allometric equation of *K. obovata* described above to estimate the mangrove biomass in the Guandu wetland. The C content of the dried materials was also analysed using an elemental analyser (Elementar vario EL III CHNOS Rapid F002, Heraeus, Germany) after grounding the materials to a fine powder.

2.3.3. Statistical analysis

A one-way ANOVA model was applied to test whether the H and $D_{0.1}$ of mangrove trees differed among measuremet times and whether organic C content differed among mangrove structures. Before the analysis, these values were examined by the rule given by Clarke and Warwick (2001) to conform to normality and homogeneity of variance assumptions. When significant differences were detected in the model, Tukey's posthoc tests were used to determine individual mean differences ($\alpha = 0.05$).

3. Results

3.1. Partial mangrove removal to decrease flood level

Our results indicated that upstream flow discharge had little effect on the rising flood level in the estuary. The 200-year return period flood in the Guandu wetland shows a slightly higher rise in flood level than the other return period floods. In addition, the simulation results of different water stages indicate that the variations in downstream water stage in the estuary did not noticeably affect the flood level.

Because the Guandu dyke was designed to protect 5-year return period floods, we selected a 5-year flood flow discharge as the upstream condition and the related water stage of the estuary as the downstream condition. The simulation results of different water conveyance associated with different mangrove coverage show that in the Keelung River, the rising flood level would most likely occur in the reach between the upstream of the Guandu wetland and the downstream of the Bailing Bridge (Fig. 1), with a 26 cm increase (Fig. 3b). From a flood control point of view, the removal of mangroves in the Guandu wetland would result in a significant prevention of flood risk. We considered that the conveyance area decline induced by mangrove trees is the most critical factor that affects the flood level along the river.

The area and location of three mangrove removal cases are proposed in Fig. 3c. The removal of 20% of the area of mangroves was the minimum requirement to control the flood risk. Under the case of 20% mangrove removal and 5-year return period floods, the water surface elevation would drop in a range from 2 to 22 mm. However, when the removal case increased to 30% or 50%, the decreases of the water surface elevation would remain between 3 and 26 mm, revealing no noticeable difference between these removal ratios. Similar simulation results were also found in the other cases of 10- and 20-year return period floods (Shang-Shu Shih's personal observation). Therefore, we recommend that the optimal case of mangrove removal for these sites is 20% to ensure flood protection.

3.2. Establishment of allometric equations

The observed aboveground biomass was regressed against the

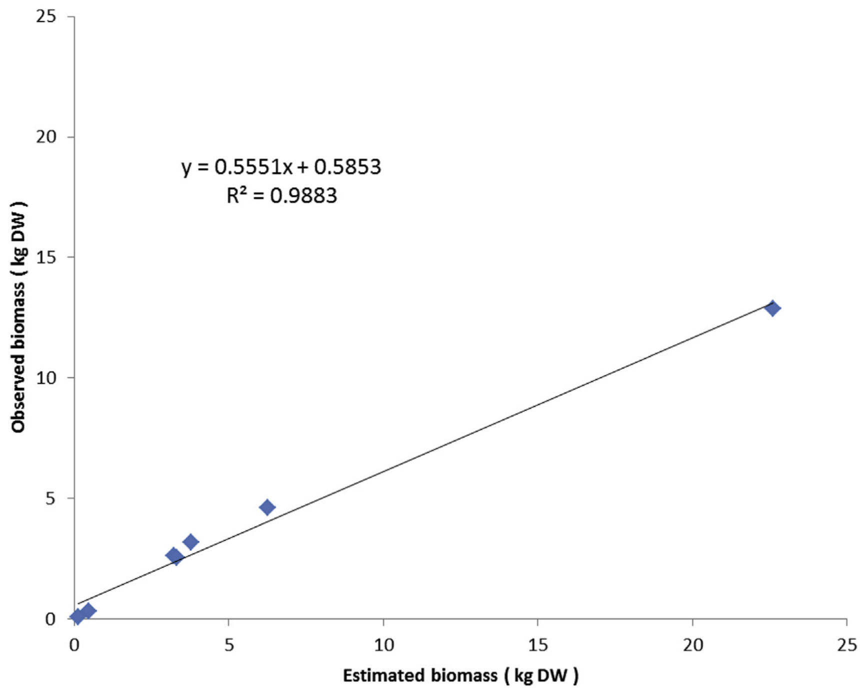

Fig. 4. The relationship between the estimated biomass derived from the allometric equation and the observed biomass of mangrove forests at Guandu in the Danshuei Estuary.

estimated aboveground biomass using the allometric equation proposed by Khan et al. (2005) for *K. obovata*. Although the explained variance is relatively high ($R^2 = 0.98$), the slope of the relationship is only 0.551 (Fig. 4), indicating that the estimated aboveground biomass is only half the observed biomass in the Danshuei Estuary. Therefore, in this study, the allometric equation for aboveground biomass was modified as Eq. (3) to better estimate the observed aboveground biomass of mangroves in the Guandu wetland.

$$\text{Aboveground biomass(kg)} = 1.765 \times 10^{-2} \times \left(D_{0.1}^2 \times H\right)^{1.058} + 0.5853 \quad (3)$$

However, the proportion of our observed belowground biomass to aboveground biomass was only 0.18 ± 0.01, which is much lower than the proportion (0.56 ± 0.03) of the same species in Okinawa, Japan based on the belowground biomass estimated by the allometric equation of Hoque et al. (2011) and the aboveground biomass estimated by the allometric equation of Khan et al. (2005). This difference can be attributed to the difficulty in harvesting all the belowground structures from the 50-cm-deep ground. Particularly for *K. obovata*, the belowground structures of an 8-cm-DBH stand may reach >1 m deep (Cuc et al., 2009). Therefore, in this study, the belowground biomass was estimated by the allometric equation proposed by Hoque et al. (2011) rather than by our own data.

3.3. Tree biomass and carbon content

The tree density in the Guandu wetland was 6533 stand ha^{-1}. The H and $D_{0.1}$ (mean ± SD) of trees were 4.42 ± 0.58 m and 10.34 ± 5.89 cm, respectively. The H measured in June and November 2012 was significantly higher than that measured in October 2011 (Fig. 5; one-way ANOVA, $P < 0.001$). However, the $D_{0.1}$ was not significantly different among the three measurement times (one-way ANOVA, $P = 0.894$). This indicates that the mangrove trees in the Guandu wetland grew higher but not thicker during the study period for over one year.

In the Guandu wetland, the calculated aboveground biomass by our modified allometric equation (Eq. (3)) was 10.73 kg DW m^{-2} in October 2011 and reached 11.85 kg DW m^{-2} in November 2012 (Fig. 5). During the study period, the calculated belowground biomass by the allometric equation of Hoque et al. (2011) changed slightly from 4.24 kg DW m^{-2}to 4.62 kg DW m^{-2}. The aboveground biomass was 2.53 times the belowground biomass, whereas the change of the aboveground biomass was 2.94 times that of the belowground biomass for over one year.

The aboveground structures of the mangrove trees in the Guandu wetland contained more C content than the belowground structures (Table 2, one-way ANOVA, $P < 0.05$). The leaves of the mangrove trees collected in the Guandu wetland contained the highest C content (mean value: 54.41%), and the roots of the mangrove trees had the lowest C content (mean value: 40.83%). Consequently, the C stored in the aboveground and belowground structures of the mangrove trees in the Guandu wetland in November 2013 was estimated to be 59.74 and 18.88 Mg C ha^{-1}, respectively (Fig. 6).

3.4. Tradeoffs between reducing flood risks and storing mangrove C stocks

The deforestation of mangrove trees is expected to remove mangrove C stocks. The removal amount of C stocks would increase with the area of mangrove deforestation. Our results show that the 20% area removal of aboveground structures of mangrove trees in the Guandu wetland would result in the loss of 0.57% of the C stocks. Furthermore, the 20% area removal of both aboveground and belowground structures of mangrove trees would decrease the C stocks by 0.74% (Fig. 7a). However, our simulation shows that the 20% area removal of mangrove trees would decrease the flood level by 6.27% (Fig. 7b). Proportionally, the 50% area removal of aboveground structures of mangrove trees would result in the loss of

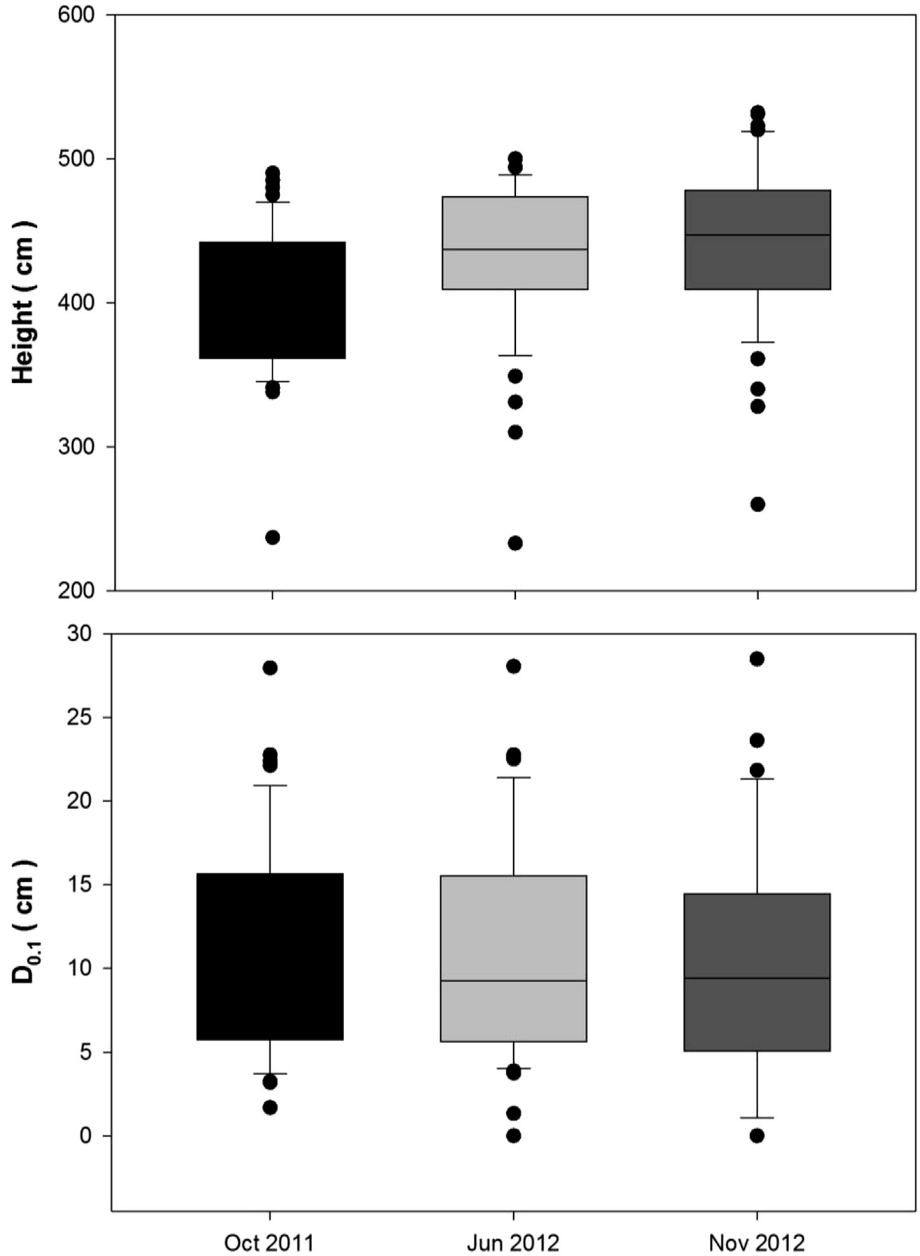

Fig. 5. Change in height and diameter of mangrove forests at Guandu in the Danshuei Estuary during the study period.

1.41% of the C stocks. However, the 50% area removal of both aboveground and belowground structures of mangrove trees would decrease the C stocks by 1.86%. The simulation also shows that 50% area removal of mangrove trees would decrease the flood level by 7.23%.

The ratios of reductions in flood levels (benefits) and the loss of mangrove C stocks (costs) were higher under the condition of the removal of only aboveground structures of mangrove trees than under the condition of the removal of both above- and belowground structures (Fig. 7c). The highest ratio (11.89) of the reduction in flood level and loss of mangrove C stocks occurs under the condition of 20% removal of aboveground structures of mangrove trees. The ratio of 11.89 is more than 2 times the ratio (5.12) under the condition of 50% removal of aboveground structures of mangrove trees. This indicates that the case of the 20% removal of only aboveground structures is the optimal way to allow the management of mangroves to meet the demands of reducing the loss of the mangrove C stocks and adequately controlling the flood risks in the Danshuei River.

4. Discussion

The ecosystem services offered by mangroves may differ depending on the location. Unlike the protection from erosion and devastation caused by tsunami-induced waves (Kathiresan and Rajendran, 2005; Walters et al., 2008) and rising sea level (Gilman et al., 2008) offered by coastal mangroves, our simulation shows that the growth of mangrove forests along the river may cause flooding threats to the nearby residential communities because they alter the flow dynamics, including lengthening the inundation duration and reducing the water conveyance area. Our study further revealed that the flood risk and sediment

Table 2
Organic carbon content (mean ± standard error, $n = 3$) of different structures of *Kandelia obovata* collected in the Guandu wetland. Letters adjacent to values denote Tukey's post-hoc differences ($p < 0.05$) when an overall difference was detected in the ANOVA model.

Kandelia obovata	Organic carbon content (%)
Leaf	54.41 ± 0.59^{a}
Branch	48.67 ± 0.76^{b}
Stem	49.42 ± 0.13^{b}
Flower	51.29 ± 0.88^{ab}
Fruit	48.27 ± 0.18^{b}
Root	40.83 ± 0.37^{c}

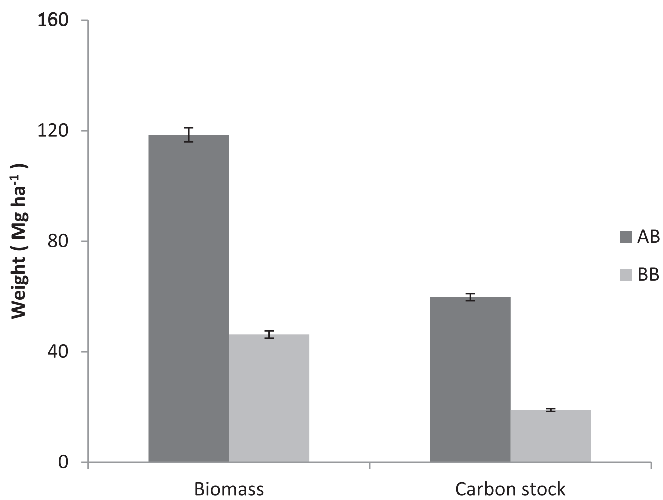

Fig. 6. Biomass and carbon stocks of the aboveground (AB) and belowground (BB) structures at Guandu in the Danshuei Estuary.

accumulation can be mitigated with the proper control of mangrove overgrowth or overexpansion. While reforestation by using mangrove forests is considered to be an important way to increase ecosystem C sequestration (Wang et al., 2013), our results show that the locations of the reforestation of mangroves should be carefully considered.

In particular, continental islands in the tropics and subtropics of the western Pacific, such as Taiwan, are characterized by mountainous watersheds, high precipitation, and high water runoff (Smith et al., 2003). Amplification of the hydrological fluctuations as a consequence of climate change has been forecasted, leading to a higher frequency of typhoons and more extreme precipitation and surface runoff (Liu et al., 2009; Lamoureux, 2000). During heavy rainfalls, rivers have a greater chance of receiving exceptionally high sediment loads. The roughness of the mangrove substrate may decrease flow velocity and increase sediment deposition (Chow, 1973), which is expected to cause increases in mangrove vegetation (Li and Shen, 1973), decreases in conveyance area and flow velocity (Lee and Shih, 2004) and thus increases in water surface levels. Consequently, the flood risk caused by the overgrowth or overexpansion of riverine mangroves would become more exacerbated under the future scenarios of climate change.

The simulation of HEC-RAS shows that mangrove tree density could affect the porosity and the resultant water conveyance area. In this model, only tree density data were incorporated to calculate the conveyance area. The mangrove forest in the Guandu wetland is a monospecific stand of *K. obovata*, and the structure is uniform. The tree density was 6533 stands ha^{-1} or 0.65 stands m^{-2}, suggesting that the average distance between trees in the forest was >1 m. The standard deviation of the H was small (0.58 m), and the standard deviation of the $D_{0.1}$ (5.89 cm) was also relatively small compared to the distance between trees. Our survey data show that *K. obovata* grew higher but showed little evidence of becoming thicker during the study period for over one year. It appears that the change in mangrove forest structure with time in the Danshuei Estuary is mainly shown in changes in tree height, rather than in tree diameter, when the tree height is > 3 m. It appears that the effect of the incorporation of variation in tree diameter data in HEC-RAS for the calculation of the conveyance area can be ignored.

By applying the allometric equation proposed by Khan et al. (2005) for *K. obovata* in Okinawa, the estimated aboveground biomass is only half the observed biomass in the Guandu wetland, although the explained variance is high. The estimated aboveground biomass derived from the allometric equation is dependent upon the $D_{0.1}$ and H data. Because *K. obovata* in the Guandu wetland was only slightly higher than that in Okinawa (Khan et al., 2009; Hoque et al., 2011), the greater aboveground biomass in the Guandu wetland can be attributed to the greater $D_{0.1}$, which was approximately twice that of *K. obovata* in Okinawa.

The relatively greater $D_{0.1}$ of the mangrove trees in the Guandu wetland might be associated with age. The mean age of the mangrove trees in the Guandu wetland was estimated to be > 10 years old according to the relationship between mean $D_{0.1}$ and age of mangrove trees (Cuc et al., 2009), although the earliest record of *K. obovata* in the wetland shows the age is > 30 years old (Lin and Chiou, 1989). The forest structure parameters of *K. obovata* in the Guandu wetland were more similar to the 70-year-old *K. obovata* forest than the 6-year-old forest in Shenzhen (Lunstrum and Chen, 2014). The H, tree density, and the resultant AGB and BGB of *K. obovata* in the Guandu wetland were comparable to the 70-year-old forest in Shenzhen. The older age of the mangrove trees in the Guandu wetland might be the reason that they were approximately twice the mean diameters of the 12-year-old forest (Khan et al., 2009) and the 13-year-old forest (Hoque et al., 2011) of the same species in Okinawa.

Our results can also be applied to *K. obovata* and other mangrove species in the tropics and subtropics of the western Pacific. Although the mean diameter of *K. obovata* in Okinawa was approximately half the mean diameter in the Guandu wetland, the tree density in Okinawa was twice the density in the Guandu wetland. Consequently, the resultant AB of *K. obovata* in the Guandu wetland was comparable to those of the same species recorded in Okinawa (Khan et al., 2009; Hoque et al., 2011). The H and AB in the Guandu wetland were also similar to those of the same species in Hong Kong (Lee, 1990) and Shenzhen on the southeast coast of China (Li, 1997). In general, *K. obovata* had smaller DBH and shorter H relative to other species growing in the same region (Komiyama et al., 2008). While the forest structure of *K. obovata* in the Guandu wetland was found to affect the porosity and the resultant water conveyance area, the flood risk caused by riverine mangroves of other species should also be taken into account in response to the forecast of the amplification of the hydrological fluctuations as a consequence of climate change (Liu et al., 2009).

We also found that the organic C contents differ greatly with different structures. The leaves and flowers had >50% organic C content, whereas the roots had only approximately 40% C content, which is much lower than the range of 48%~49% organic C contained in the stems and branches. While mangroves are considered an important C-rich ecosystem (Donato et al., 2011), different factors of C content should be used for the calculation of the C stocks of above- and belowground structures of mangrove trees.

In this study, the loss of biodiversity presumably promoted by mangroves (Vo et al., 2012) due to the partial removal of mangroves

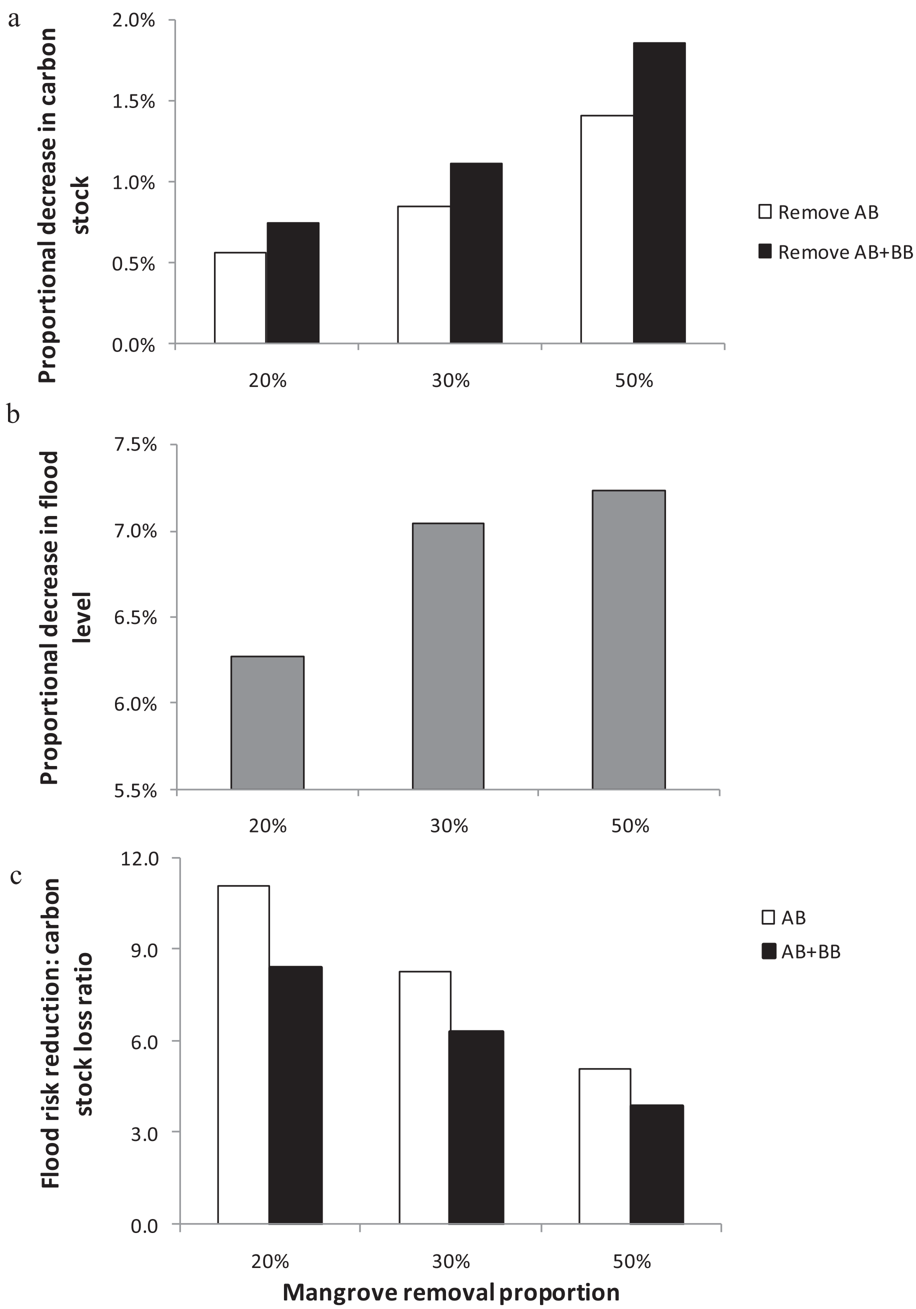

Fig. 7. (a) The proportional loss in carbon stocks that resulted from the proportional removal of aboveground structure (AB) or aboveground and belowground structures of mangrove trees (AB + BB), and (b) the proportional reduction in flood risks that resulted from the removal, and (c) the ratio of flood risk reduction and carbon stock loss that resulted from the removal.

trees was not taken into account. When mangrove trees invade bare tidal flats and gradually form a dense canopy, they block sunlight and outcompete other types of vegetation, such as benthic microalgae. Benthic microalgae or macroalgae are often the preferred food of many macrobenthos compared to refractory detritus derived from mangrove litter (Hsieh et al., 2002; Lin et al., 2007). As a result, the expansion of mangrove trees can severely change the structure and subsequently the function of an estuarine and coastal ecosystem. In the Danshuei Estuary, dense mangrove vegetation in the Shezi wetland was removed in 2007 to return the habitats back to mudflats and a tidal creek. Huang et al. (2012) concluded that controlling the spread of estuarine mangrove forests could increase biodiversity and particularly benefit the migratory shorebird community. It is likely that the partial removal of mangrove trees in the Guandu wetland may increase the biodiversity of the habitat.

One of the reasons of the exceptionally high C storage in mangrove forests is the accumulation of organic-rich soils (Donato et al., 2011). In this study, the increased water conveyance area, which resulted from the removal of mangrove trees, may flush out some of the organic C in the surface soil. The organic C content in the soil of mangroves can reach 22.3% (Saintilan et al., 2013). In the Guandu wetland, however, the organic C content was only 5.1% (Po-Hung Chen's unpublished data), which was much lower than the C contents in oceanic, coastal, and estuarine magroves (Adame et al., 2013; Donato et al., 2011; Kauffman et al., 2011; Wang et al., 2013). Riverine mangroves have been shown to export more organic C than other types of mangroves, such as fringe mangroves and basin mangroves (Twilley et al., 1986). It is likely that the lower organic C content in the soil of mangroves in the Guandu wetland is a result of the frequent flushing by the riverwater. From our perspective, the loss of organic C in the soil as a result of increased water conveyance area due to the partial removal of riverine mangrove trees would be relatively minor.

The management of mangroves should consider the probability of success (e.g., removal of aboveground biomass only) and the costs and benefits of the project. We suggest that both high and low levels of density or coverage of mangrove trees will lead to reduction of certain ecosystem services. We reasoned that if the mangrove tree density or coverage is high, the ecosystem services provided by C sequestration and stocks will be increased. However, we also predict that the ecosystem services provided by biodiversity will decrease and the flood risk will increase. These relationships may not be linear. We suggest that at some intermediate level of mangrove tree density or coverage, where there are enough mangrove trees to uptake and store C but not enough trees to reduce biodiversity and increase flood level, the system may provide the best balance of ecosystem services that meet the demands of human wellbeing. Although the tradeoffs of ecosystem services are not uniform, the management of mangroves can be achieved in an optimal way.

5. Conclusions

This research provides a case study exhibiting the tradeoffs between ecosystem services in mangrove management. Our simulation shows that the growth of mangrove forests along the Danshuei River may cause flooding threats to the nearby residential communities. However, the flood risk can be mitigated with partial mangrove removal. Our results show that the highest ratio of the effective reduction in flood level and the loss of mangrove C stocks occurred under the condition of removal of 20% of aboveground structures of mangrove trees, indicating the optimal removal area for mangrove management in the river.

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