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Biomass accumulation and organic carbon stocks of *Kandelia obovata* mangrove vegetation under different simulated sea levels

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Abstract

Mangrove forests are vulnerably threatened by sea level rise (SLR). Vegetation organic carbon (OC) stocks are important for mangrove ecosystem carbon cycle. It is critical to understand how SLR affects vegetation OC stocks for evaluating mangrove blue carbon budget and global climate change. In this study, biomass accumulation and OC stocks of mangrove vegetation were compared among three 10 year-old *Kandelia obovata* (a common species in China) mangrove forests under three intertidal elevations through species-specific allometric equations. This study simulated mangrove forests with SLR values of 0 cm, 40 cm and 80 cm, respectively, representing for the current, future ~100 a and future ~200 a SLR of mangrove forests along the Jiulong River Estuary, China. SLR directly decreased mangrove individual density and inhibited the growth of mangrove vegetation. The total vegetation biomasses were (12.86±0.95) kg/m^2, (7.97±0.90) kg/m^2 and (3.89±0.63) kg/m^2 at Sites SLR 0 cm, SLR 40 cm and SLR 80 cm, respectively. The total vegetation OC stock decreased by approximately 3.85 kg/m^2 (in terms of C) from Site SLR 0 cm to Site SLR 80 cm. Significantly lower vegetation biomass and OC stock of various components (stem, branch, leaf and root) were found at Site SLR 80 cm. Annual increments of vegetation biomass and OC stock also decreased with SLR increase. Moreover, significant lower sedimentation rate was found at Site SLR 80 cm. These indicated that SLR will decrease mangrove vegetation biomass and OC stock, which may reduce global blue carbon sink by mangroves, exacerbate global warming and give positive feedback to SLR.

Key words: sea level rise, vegetation biomass, organic carbon stock, component, mangrove forest, *Kandelia obovata*

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1 Introduction

Mangrove forests are a valuable coastal ecosystem in the subtropical and tropical areas due to their important ecosystem services, such as habitats for coastal and marine biodiversity, commercial fisheries, coastal protection, high production and rich organic carbon (OC) storage (Donato et al., 2011; Alongi, 2014). The global mean net primary production of mangroves is estimated as 1 363 g/(m^2·a), exceeding other marine ecosystems, for example, salt marshes, seagrasses, macroalgae and coastal phytoplankton (Bouillon et al., 2008; Alongi, 2014). Compared to terrestrial ecosystems, mangrove forests are the most carbon-dense coastal vegetated ecosystems due to their higher productivity (Donato et al., 2011; Kauffman et al., 2016). The average ecosystem OC stock is 956 Mg/hm^2, storing three to five times more carbon than terrestrial forests (Donato et al., 2011; Alongi, 2014). Although the area of global mangrove is less than 2% area of main land, it contains about 10%–15% of total carbon burial in marine environments (Breithaupt et al., 2012; Pérez et al., 2017; Chen et al., 2018). Considered with global climate change, reduction of carbon loss in mangrove wetlands and increase of existing carbon pools for carbon sequestration are important for the atmospheric cooling effect and climate change mitigation (Duarte et al., 2013; Chen et al., 2016). Carbon stored in mangrove ecosystems, along with salt marshes and seagrass beds, is termed “blue carbon” and has become a topic of global interest (Capooci et al., 2019).

Due to land use changes (conversion of mangroves to aquaculture, agriculture, urban, tourism and industrial uses) and global climate change resulting from the increases in the atmospheric CO$_2$ concentration and temperature, there has been a massive reduction in the global mangrove area in the past decades (Sippo et al., 2018; Mafi-Gholami et al., 2020; Wu et al., 2020). When governments and publics realized the importance of mangrove forests, especially carbon sink capacity, mangrove res-

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toration projects were performed around the world to compensate for the loss of mangroves and to increase the existing carbon pools for carbon sequestration (Duarte et al., 2013; Chen et al., 2016). However, global warming is the biggest challenge for mangroves compared with land use change. Sea level rise (SLR) is a major consequence of global warming (Perera et al., 2018). Based on the Representative Concentration Pathway Scenarios (RCPS), projected average increases in sea levels range from 50 cm to 100 cm by the end of the 21st century, following the drastic emissions reductions (RCP 2.6) or unmitigated growth of emissions (RCP 8.5) pathways, respectively, and may even reach 2 m by the end of the 21st century (Horton et al., 2014; Mafi-Gholami et al., 2020). SLR will increase seawater depth, change water movement, alter tidal variation, and increase seawater intrusion into mangrove forests, resulting in both deep flooding level, long flooding duration and anaerobic condition (Ye et al., 2010; Wang et al., 2019). As the only forest between land and sea, mangrove forests constitute one of the first ecosystems vulnerable to SLR (Krauss et al., 2014; Chen and Wang, 2017).

Based on existing researches, mangrove forests may be unable to keep pace with ongoing and projected SLR which becomes the main threat for mangrove ecosystems (the current and expected extent/area and health) all over the world (Gilman, 2008; Lovelock et al., 2015; Sippo et al., 2018). On the one hand, permanent inundation of mangrove roots for a long period of time could possibly deprive the roots of air (relevant adaptations may not be adequate to withstand such a situation) and cause death of the plants (Perera et al., 2018). On the other hand, long term inundation declines mangrove seedings biomass and changes relative growth rates of both *Kandelia obovata* and *Bruguiera gymnorrhiza* according to few previous studies (Ye et al., 2004; Lu et al., 2013). SLR resulting in long term inundation may affect growth and biomass allocation of mangrove plant seedlings. Mangrove vegetation OC stocks are related with vegetation biomass and SLR may affect vegetation OC stocks of mangrove forest ecosystems. OC saved in the whole mangrove ecosystem was consisted of soil OC stock and vegetation OC stock. Although our previous study (Chen et al., 2020b) has reported that SLR could increase soil OC stock in mangrove forests and contribution of mangrove carbon to soil OC. Direct field observations for responses of biomass accumulation and OC stocks of mangrove vegetation to SLR remain unexplored, creating a significantly uncertainty on the OC stocks of the whole mangrove ecosystem.

Changes in the OC stocks of the whole mangrove ecosystem caused by SLR will alter the impacts of mangrove on global blue carbon budget and climate change mitigation. Therefore, in the present study, biomass accumulation and OC stocks of mangrove vegetation due to SLR were quantified in three *K. obovata* (a common species in China) mangrove forests under three intertidal elevations. We posed the following four scientific questions: (1) How will SLR affect tree density and growth parameters of mangrove forests? (2) How will SLR affect mangrove vegetation biomass accumulation? (3) How will the changes in mangrove vegetation biomass accumulation with SLR affect mangrove vegetation OC stock? (4) How will the changes in mangrove vegetation OC stock with SLR affect mangrove blue carbon budget and climate change mitigation?

2 Materials and methods

2.1 *Study area and plot arrangements*

The study area (24°33′9.24″N, 118°02′3.71″E) is situated on the coastline of Zengying, in Xiamen, Fujian, China (Fig. 1). According to our previous studies, annual mean rainfall is 1 097 mm, with most rainfall occurring from April to October. The extreme high air temperature is 36.1°C and the extreme low air temperature is 3.8°C. Annual mean air temperature is 20.8°C and annual total sunshine time is 2 276 h (Chen and Ye, 2014; Chen et al., 2020b). Annual mean seawater surface temperature is 22.0°C (Local Chronicles Office of Xiamen Municipal People's Government, 2014, 2015). Tides are semidiurnal, with an average range of 4 m, and seawater adjacent to mangrove area with salinities range from 26 to 30 (Chen and Ye, 2014). Altitude of local mean sea level in the Xiamen Bay is 365 cm (Ruan et al., 2010).

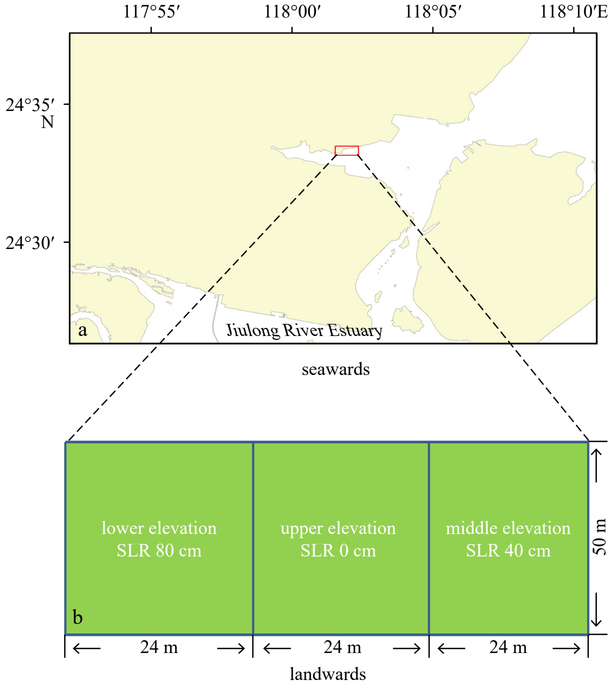

Fig. 1. The study area in Zengying (a); size and distribution of the three study sites (b).

Before 2002, many aquaculture ponds with boulder strips in intertidal zones were used for crab breeding to fill human's demand for aquatic products. After 2002, these crab ponds were deserted and cofferdams around ponds were demolished. Since the beginning of 2004, mangrove ecological restoration project in the coastal zone has been started in this region. Three adjacent ponds were transformed for mangrove plantations and how to transform these three ponds has reported in our previous studies (Chen and Ye, 2014; Chen et al., 2020b). In brief, soils with similar properties beside these ponds were used to transform mangrove planting sites and the final steady differences in elevation between two nearby sites were 40 cm, with the sea level altitudes of 335 cm (SLR 80 cm), 375 cm (SLR 40 cm) and 415 cm (SLR 0 cm) for the lower (L), middle (M) and upper (H) elevations, respectively. According to National Oceanographic Information Center, Ministry of Natural Resources, China (2019), average increase in sea level rise in China was 3.3 mm/a from 1980 to 2018. Sea levels at Sites SLR 0 cm, SLR 40 cm and SLR 80 cm simulated the current, future ~100 a and future ~200 a SLR of mangrove forests along the Jiulong River Estuary approximately 22 km away from this study area. an important *K. obovata* area, Fujian, China. Mean inundation times were 10 h/d, 8 h/d and 6 h/d (i.e., 5 h, 4 h and 3 h per tide) at Sites SLR 80 cm, SLR 40 cm and SLR 0 cm, respectively, measured during one whole tide period of 15 d in August 2004 (Chen and Ye, 2014). Prior to seedling plantation, soil physicochemical properties were measured and soils at the three sites had similar soil physicochemical properties (Chen et al., 2020b). *Kandelia obovata* and *Avicennia marina* were planted at the three areas in May 2004, with additional details regarding mangrove plantations shown in Chen and Ye (2014). *Kandelia obovata* among the three sites became dominant species and had the same forest age (10 a-old) at the sampling time of the present study.

2.2 *Field investigation and sampling*

Each experimental mangrove site was small and even with regular plantations and an area of approximately 1 200 m^2. There were no dead trees found at the three sites based on field observation during the sampling time. Therefore, tree density investigation was only done on May 18, 2013, and three 4 m×4 m plots were set up in the center of each site to investigate tree density. On May 18, 2014, different fresh components of mangrove vegetation samples (stem, branch, leaf and root) were collected from each site for OC content analysis to estimate OC stocks of different components and the total vegetation. These samples were washed and dried at 60°C to constant weight. At each site, eleven individual trees with similar growth parameters were selected and marked, to investigate growth parameters including tree height, breast diameter, branch height and crown width on May 18, 2013 and on May 18, 2014.

Compared to destructive methods for estimating vegetation biomass and carbon storage capacity, non-destructive methods are becoming increasingly popular as they do not harm individual trees or ecosystems. In the present study, mangrove vegetation biomass including aboveground biomass (stem biomass, branch biomass and leaf biomass) and belowground biomass (root biomass) was estimated using the species-specific allometric equations as shown in the research of Tam et al. (1995). Stem biomass, branch biomass, leaf biomass and root biomass were calculated by the following formula:

$$\log_{10} WS = 2.162 + 0.869 \log_{10}(D^2H), \tag{1}$$

$$\log_{10} WB = 2.741 + 1.253 \log_{10}(D^2H), \tag{2}$$

$$\log_{10} WL = 1.706 + 0.943 \log_{10}(D^2H), \tag{3}$$

$$\log_{10} WR = 2.433 + 0.990 \log_{10}(D^2H), \tag{4}$$

where D (m) was breast diameter; H (m) was tree height; WS (kg) was stem biomass; WB (kg) was branch biomass; WL (kg) was leaf biomass; WR (kg) was root biomass.

Annual vegetation biomass increments were calculated by the following formula:

$$\mathrm{ABI} = B_{2014} - B_{2013}, \tag{5}$$

where ABI (kg/(m^2·a)) was annual vegetation biomass increments; B_{2014} was mangrove vegetation biomass in 2014 and was calculated by breast diameter and tree height measured in 2014; B_{2013} was mangrove vegetation biomass in 2013 and calculated by breast diameter and tree height measured in 2013.

2.3 *Chemical analyses*

Rapid dichromate oxidation procedure was used to measure OC content of mangrove vegetation. OC stocks of mangrove vegetation were calculated by the following formula:

$$V_{\mathrm{s}} = V_{\mathrm{c}} V_{\mathrm{b}}, \tag{6}$$

where V_{s} (kg/m^2, in terms of C) was OC stocks of mangrove vegetation (including stem, branch, leaf and root, respectively); V_{c} (%) was OC content of mangrove vegetation; V_{b} (kg/m^2) was vegetation biomass.

Annual vegetation OC stock increments were calculated by the following formula:

$$\mathrm{ACI} = C_{2014} - C_{2013}, \tag{7}$$

where ACI was annual vegetation OC stock increments (kg/(m^2·a), in terms of C); C_{2014} was vegetation OC stock in 2014 and calculated by vegetation biomass in 2014; C_{2013} was vegetation OC stock in 2013 and calculated by vegetation biomass in 2013.

2.4 *Field sedimentation experiment*

During the entire experiment, self-made sediment trap was used to perform field sedimentation experiment. In brief, the nylon filter membrane (with a diameter of 180 mesh) fixed at smooth port of PVC tubes (inner diameter of 10 cm, length of 20 cm) with small holes on the pipe (to ensure the flow of water inside and outside the tube) was used to measure sedimentation rates. According to tide regular pattern of sampling sites, a complete tide cycle was about 7 d (4 times per month, 48 times per year). Before the beginning of a complete tide cycle, three plots were randomly selected at each site and 4 traps were randomly set at each plot. These traps were retrieved on the day after the end of a complete tide cycle. Retrieved filter membrane was air-dried and weighed. Surface soil was sampled at each point to convert the bulk density for calculating sedimentation rates (thickness, mm/a).

2.5 *Statistical analyses*

Normality of each variable was examined using Kolmogorov-Smirnov test. Effects of SLR on the tree density, growth parameters, vegetation biomass and OC stocks, aboveground biomass/belowground biomass (AB/BB), annual increments of vegetation biomass and OC stocks, and sedimentation rates were analyzed using a one-way analysis of variance (ANOVA). All statistical analyses were performed using SPSS 22.0 for Windows (SPSS, USA).

3 Results

3.1 *Vegetation structure*

As shown in Fig. 2, tree density was (2.33±0.31) trees/m^2, (2.75±0.54) trees/m^2 and (4.08±0.51) trees/m^2 at Sites SLR 80 cm, SLR 40 cm and SLR 0 cm, respectively. SLR had significant effects on this parameter (F=7.681, P=0.022) and the highest value was found at Site SLR 0 cm. Similar to tree density, SLR also had significant impacts on the tree height (F=106.635, P<0.001) and breast diameter (F=14.236, P<0.001), with the lowest values measured at Site SLR 80 cm. However, branch width (F=0.936, P=0.403) did not differ among the three sites and the value was (72.10±17.85) cm, (80.21±24.26) cm and (86.82±28.88) cm at Sites SLR 80 cm, SLR 40 cm and SLR 0 cm, respectively. Crown width (F=4.038, P=0.028) at Site SLR 40 cm was significantly lower than that at other two sites, and the values ranged from (46.41±9.00) cm to (64.05±13.89) cm.

3.2 *Vegetation biomass and annual vegetation biomass increments*

Significant difference of total biomass (F=288.330, P<0.001) was found among the three sites in 2014 with values of (3.89± 0.63) kg/m^2, (7.97±0.90) kg/m^2 and (12.86±0.95) kg/m^2 at Sites

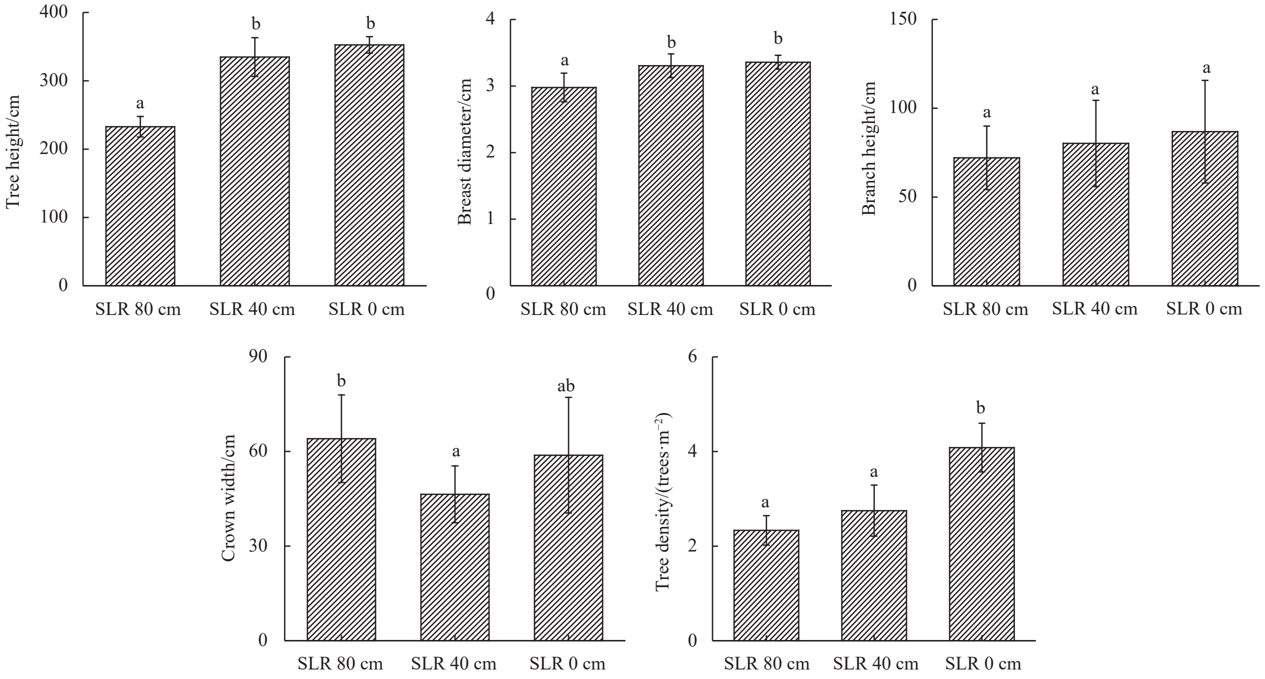

Fig. 2. Growth parameters of three *Kandelia obovata* forests (different letters for each parameter indicate a significant difference at $P<0.05$).

SLR 80 cm, SLR 40 cm and SLR 0 cm, respectively (Fig. 3). Significantly lower aboveground biomass ($F=289.426$, $P<0.001$) and root biomass ($F=286.366$, $P<0.001$) were found at Site SLR 80 cm. Compared to these parameters at Site SLR 0 cm, the values decreased by approximately 5.72 kg/m^2 and 3.26 kg/m^2, respectively (Fig. 3). Like the tendencies of total biomass, aboveground biomass and root biomass, components (stem, branch and leaf) of aboveground biomass were also affected by SLR (stem ($F=331.528$, $P<0.001$), branch ($F=221.320$, $P<0.001$), leaf ($F=302.318$, $P<0.001$)). The lowest biomass of stem, branch and leaf reached (1.58±0.23) kg/m^2, (0.56±0.12) kg/m^2 and (0.35±0.06) kg/m^2 at Site SLR 80 cm (Fig. 3). In addition, SLR also had significant effects on the AB/BB ($F=55.845$, $P<0.001$) with the value ranged from 1.76±0.00 to 1.78±0.01.

Annual increments of total biomass ($F=51.493$, $P<0.001$), aboveground biomass ($F=51.708$, $P<0.001$), root biomass ($F=51.118$, $P<0.001$) and different components (stem ($F=45.431$, $P<0.001$), branch ($F=63.760$, $P<0.001$) and leaf ($F=48.889$, $P<0.001$)) of aboveground biomass were all affected by SLR. These parameters decreased with SLR increase, and the values decreased by approximately 0.841 kg/(m^2·a) (total), 0.536 kg/(m^2·a) (aboveground), 0.306 kg/(m^2·a) (root), 0.276 kg/(m^2·a) (stem), 0.190 kg/(m^2·a) (branch) and 0.070 kg/(m^2·a) (leaf) from Site SLR 0 cm to Site SLR 80 cm, respectively (Fig. 3).

3.3 *Vegetation OC content*

As shown in Fig. 4, leaf OC contents ($F=8.909$, $P=0.016$) significantly varied with SLR and the value was 43.35%±1.58%, 48.27%±3.21% and 39.46%±0.56% at Sites SLR 80 cm, SLR 40 cm and SLR 0 cm, respectively. However, there were no significant

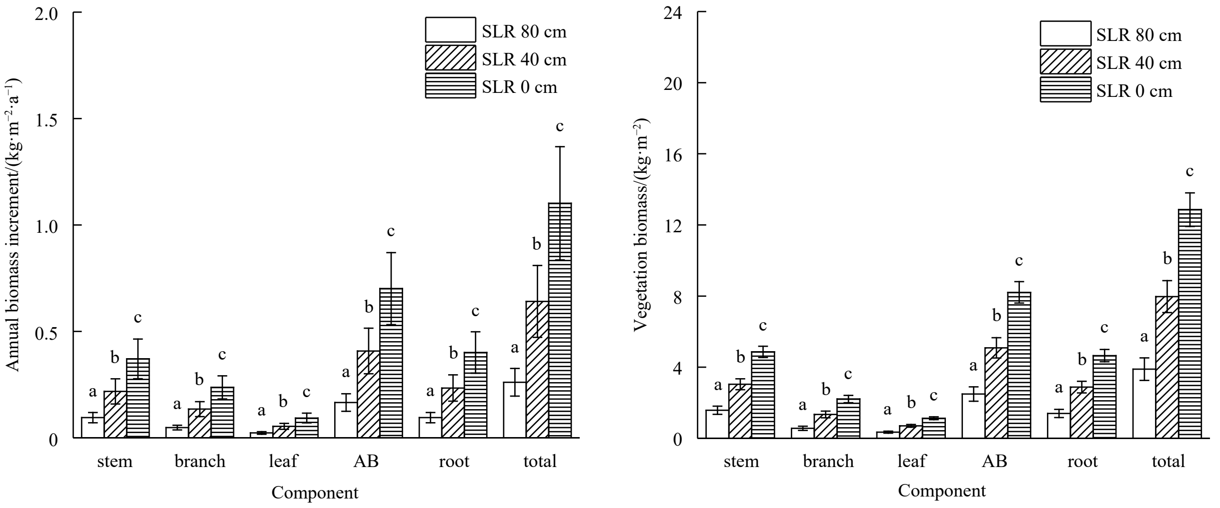

Fig. 3. Annual biomass increment and vegetation biomass of different components (stem, branch, leaf, aboveground (AB), root and total) of three *Kandelia obovata* forests (different letters for each parameter indicate a significant difference at $P<0.05$).

effects between other mangrove components (stem (F=4.880, P=0.055), branch (F=0.941, P=0.441) and root (F=1.155, P=0.376)) and SLR. OC contents of these parameters ranged from 40.30%±0.42% to 49.60%±1.86%.

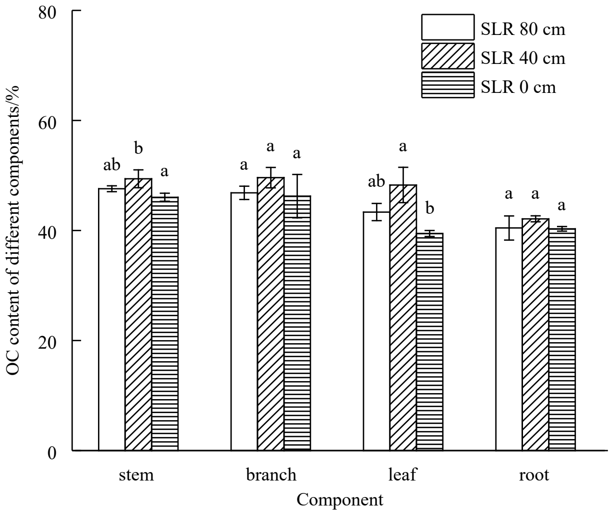

Fig. 4. Organic carbon (OC) contents of different components (stem, branch, leaf and root) of three *Kandelia obovata* forests (different letters for each parameter indicate a significant difference at P<0.05).

3.4 *Vegetation OC stock and annual vegetation OC stock increment*

Significant differences of total OC stock (F=262.928, P<0.001), aboveground OC stock (F=257.340, P<0.001), root OC stock (F=274.514, P<0.001), stem OC stock (F=298.322, P<0.001), branch OC stock (F=206.475, P<0.001) and leaf OC stock (F=229.306, P<0.001) were found among the three sites. Total OC stock was (1.73±0.28) kg/m^2 (in terms of C), (3.72±0.42) kg/m^2 (in terms of C) and (5.58±0.41) kg/m^2 (in terms of C) at Sites SLR 80 cm, SLR 40 cm and SLR 0 cm, respectively (Fig. 5). Similar to total OC stock, significantly lower aboveground OC stock, root OC stock, stem OC stock, branch OC stock and leaf OC stock were measured at site SLR 80 cm, and the values were (1.17±0.19) kg/m^2 (in terms of C), (0.57±0.09) kg/m^2 (in terms of C), (0.75±0.11) kg/m^2 (in terms of C), (0.26±0.06) kg/m^2 (in terms of C) and (0.15±0.02) kg/m^2 (in terms of C), respectively (Fig. 5). Moreover, these parameters decreased with SLR increase.

Similar to annual vegetation biomass increment, SLR had significant impacts on the annual increments of total OC stock (F=48.435, P<0.001), aboveground OC stock (F=47.880, P<0.001), root OC stock (F=49.568, P<0.001), stem OC stock (F=42.336, P<0.001), branch OC stock (F=60.579, P<0.001) and leaf OC stock (F=40.518, P<0.001). The values of these parameters ranged from (0.01±0.00) kg/m^2 (in terms of C) and (0.48±0.12) kg/m^2 (in terms of C) and the lowest annual increments of these parameters were also obtained at Site SLR 80 cm (Fig. 5).

3.5 *Sedimentation rates*

Sedimentation rates were (1.741±0.005) mm/a, (0.455±0.006) mm/a and (0.169±0.053) mm/a at Sites SLR 0 cm, SLR 40 cm and SLR 80 cm, respectively. SLR had significant effects on this parameter (F=740.707, P<0.001).

4 Discussion

4.1 *Vegetation structure*

Mangrove forests grow in the intertidal region of the tropical and subtropical coasts with low wave energy (Wang et al., 2020). SLR caused by global climate change increases seawater depth, changes water movement, alters tidal variation, and increases seawater intrusion into mangrove forests (Ye et al., 2010; Wang et al., 2019). Both deep flooding level and long flooding duration due to SLR will change coast wave energy which may affect survival rate and growth of mangrove forests. The three sites had the same plantation density of 4 trees/m^2 (Chen and Ye, 2013). Ten years after plantation in the present study, vegetation density at Site SLR 0 cm was similar to planting density while significantly lower tree density was found at Sites SLR 80 cm and SLR 40 cm. Mangrove survival rate decreased with SLR and three reasons may be taken in consideration. On the one hand, deep flooding conditions owing to SLR lead to a lack of oxygen supply, which could deprive roots of air and cause death of the plants (Perera et al., 2018). On the other hand, growth and physiological re-

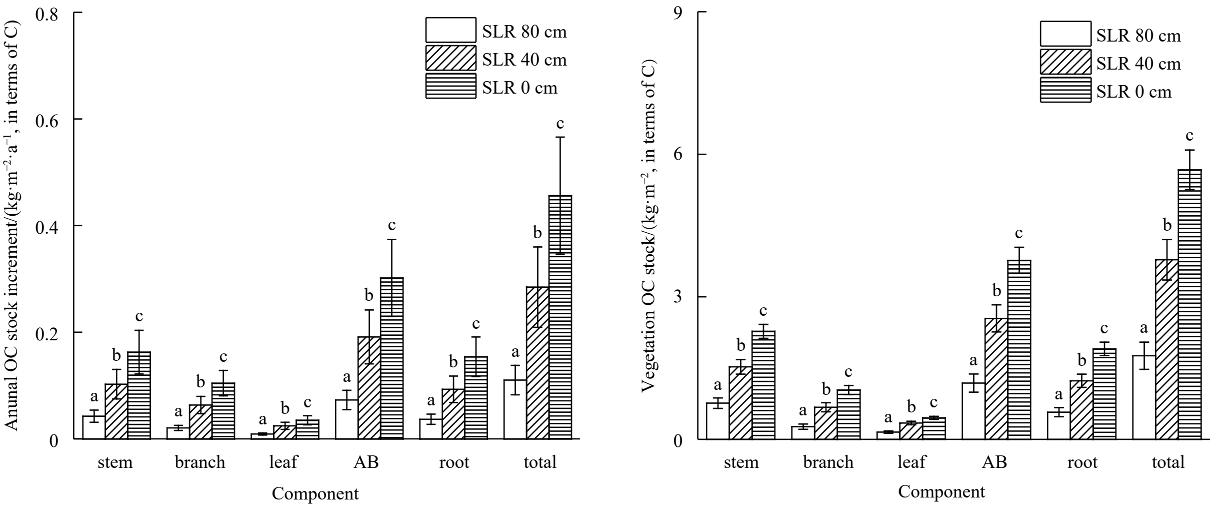

Fig. 5. Annual organic carbon (OC) stock increments and vegetation OC stocks of different components (stem, branch, leaf, aboveground (AB), root and total) of three *Kandelia obovata* forests (different letters for each parameter indicate a significant difference at P<0.05).

sponses of *K. obovata* seedlings under deep flooding conditions varied with salinity level; growth was enhanced at the low salinity level but inhibited at the high salinity level (Ye et al., 2010). Finally, salinity increase caused by SLR may be more conducive to the survival of the fouling barnacles (Yang et al., 2013). Barnacles affect the photosynthetic rate and eventually reduce the growth and survival of mangroves by attaching to the leaves and stems of mangrove plants, hindering the normal gas and nutrient exchange of plants, especially in seedlings and juvenile individuals (Li et al., 2009). Therefore, SLR decreased mangrove tree density.

Furthermore, although the forests survived at the three sites, their growth parameters had significant responses to SLR. Prolonged flooding time inhibited the growth of plants (Perera et al., 2018), resulting in short plant and sparse forest at Site SLR 80 cm. The result in the present study answered the first scientific question, and SLR will decrease tree density and growth parameters of mangrove forests. In order to compensate for the loss of mangroves and to increase the existing carbon pools for carbon sequestration, mangrove restorations have been performed around the world. However, some restoration areas are in the mid and low tidal zones, such as the Jiulong River Estuary, South China (Chen et al., 2020a), and mangrove forests in these areas will be affected by SLR firstly. SLR will decrease survival rate and growth parameters of mangrove forests, even cause death of mangrove vegetation. Therefore, effect of SLR on the survival rate and growth parameters of mangrove forests which may lead to afforestation failure should be considered in the future mangrove restorations.

4.2 *Vegetation biomass*

Mangrove production was greatly associated with the surrounding environment (Munns and Tester, 2008; Hossain et al., 2017). In the present study, SLR not only decreased survival rate and growth parameters of mangrove forests, but also decreased vegetation biomass. Firstly, due to deep flooding conditions caused by SLR, annual vegetation biomass increments of stem, branch, leaf and root followed the order of SLR 80 cm<SLR 40 cm< SLR 0 cm, resulting in the lowest total biomass found at Site SLR 80 cm. Secondly, based on microscopic mechanism, SLR would affect the number of stomata, maximum photosynthetic rate, and relative growth rate of mangrove plants (Ellison and Farnsworth, 1997), leading to the decrease of total biomass among the three sites. Finally, sedimentation was another important biogeochemical process in mangrove forests. In the present study, mangrove community structure (e.g., tree density), which was conducive to enhancing sedimentation, decreased with SLR, resulting in the lowest sedimentation rate at Site SLR 80 cm. The trend of sedimentation rate with SLR led to harsh environment for vegetation growth directly, answering the phenomenon that the lowest total biomass was found at Site SLR 80 cm.

Besides total biomass, components of total biomass had significant responses to SLR. For root (BB), additional water applied to an environment that already has adequate moisture may in fact reduce root lifespan, as the frequency of anaerobic conditions elevates root stress and pressures from external factors including soil pathogens and saprophytic fungi increase (Leppälammi-Kujansuu et al., 2014). Root biomass decreased with SLR for adapting flooding, which would be expected to decrease the oxygen demand by root tissues, shorten the oxygen diffusion path to the growing root tips, and decrease the requirement of oxygen for external rhizosphere oxidation (Ye et al., 2004). Furthermore, Redox potential of mangrove soil is less than –200 mv and mangrove soil water content is higher than other forests, making the roots in a state of long-term hypoxia (Pupin and Nahas, 2015; Otero et al., 2017). Through long-term evolution, mangrove root system can be well adapted to the conditions of substrate oxygen deficiency. Nevertheless, this ability has certain limits. When flooding time exceeding a certain threshold, it will affect its biomass, photosynthetic rate, and survival rate of seedlings (Kitaya et al., 2002; Chen et al., 2004). Therefore, long-term flooding caused by SLR inhibited vegetation growth and lower root biomass was found at Site SLR 80 cm.

Regarding aboveground biomass, different components (stem, branch and leaf) of aboveground biomass have been adjusted to adapt prolonged flooding due to SLR. Although biomass of these parameters decreased with SLR. The contribution rates of stem and leaf to total biomass were up to the highest value (40.6% and 9.0%) at Site SLR 80 cm. Leaf litter generally comprised most of litter production and thus potentially played a substantial role in the carbon cycling and sequestration in mangrove forests and their adjacent coastal areas (Ye et al., 2013; Chen et al., 2020a). Mangrove forests exported a majority of their leaf litter production (more than 66.5%) providing a large amount of OC to their adjacent ecosystems (Chen et al., 2020a). The changes of contribution rate of leaf to total biomass will result in more leaf litter entered into adjacent ecosystems which will change the process of OC in mangrove ecosystem and be not conducive to coping with SLR. At the same time, AB/BB ratio also increased with SLR to adapt long flooding duration, agreeing with our previous study (Ye et al., 2004). These results were responded to our second scientific question. SLR will decrease total vegetation biomass and other component biomass, and change contribution rate of each component biomass to total vegetation biomass.

Through simulating different sea levels, the study found the differences in the total vegetation biomass and other component biomass with SLR. However, SLR is a long-term (more than 100 a) slow process and the adaptation of mangroves to SLR is also a slow process. The slow process of the adaptation of mangroves to SLR was not considered in this study. In addition, sea levels were different at the different areas, and sea level may even reach 200 cm by the end of the 21st century based on RCPS (Mafi-Gholami et al., 2020). In the present study, data of SLR were only based on the average increase in sea level in China and only one mangrove species was considered. Considering with complexity of sea level rise, without a doubt, more samples should be collected at the different areas with different SLR conditions or different mangrove species response to SLR to fully clarify the effects of SLR on the total vegetation biomass and other component biomass in the next studies.

4.3 *Vegetation carbon stock*

Mangrove forests could provide important ecosystem services for human, and mangrove vegetation biomass is a good proxy of the magnitude of ecosystem services they will provide (Kauffman and Donato, 2012; Howard et al., 2014). Many important coastal wetland ecological functions and services are affected by the changes in mangrove vegetation biomass, structure and productivity, like carbon storage (Yáñez-Espinosa et al., 2001; Krauss et al., 2006). Although OC content of each component was not affected by SLR, except leaf. The lowest total vegetation OC stock and each component OC stock were found at Site SLR 80 cm. The changes in the vegetation OC contents and vegetation biomass following SLR suggested that the decreases in the total vegetation OC stock and each component OC stock with SLR were attributed to mangrove vegetation biomass decrease, replying our third question that reduction of mangrove vegetation biomass decreased vegetation OC stock. Carbon sinks of mangrove forests fluctuate widely owing to the influences of tidal amplitude (Kelleway et al., 2016; Gao et al., 2019). The result in the present study was similar to former study that the accumulation of OC in the vegetation can be increased because of the reduction in tide erosion with the increase in the distance from the shore (Donato et al., 2011; Wang et al., 2013). Carbon in mangrove forest was important for the atmospheric cooling effect and climate change mitigation. The change in mangrove vegetation OC stock because of SLR may be unable to mitigate global climate change and made a positive feedback to SLR, which warrants attention.

Although mangrove vegetation OC stock decreased with SLR, mangrove soil OC stock increased with SLR in our previous study (Chen et al., 2020b). The trends of these two parameters with SLR were different. Mangrove litter decomposition and production were substantially associated with surrounding environment (Munns and Tester, 2008; Hossain et al., 2017; Liu et al., 2017). Mangrove surrounding environment changed by SLR not only decreased mangrove production which decreased mangrove vegetation OC stock, but also may promote leaf litter and roots decomposition which increased mangrove soil OC stock. This also conformed our previous conclusion (Chen et al., 2020b) that SLR will increase mangrove contribution to soil OC. Specific effect of SLR on the leaf litter and root decomposition should be considered in the next studies.

Moreover, some questions should be considered based on the whole blue carbon stock in mangrove ecosystem. Firstly, tree density and growth parameters of mangrove forest decreased with SLR. Though mangrove forests could live at Sites SLR 80 cm and SLR 40 cm. Some studies projected average increases in sea levels may even reach 2 m by the end of the 21st century (Mafi-Gholami et al., 2020). In most areas, there are many seawalls behind mangrove forests, such as mangrove forests along the Jiulong River Estuary, an important *K. obovata* area in Fujian, China. Mangrove forests in these areas may be unable to migrate from sea to land and to keep pace with SLR, leading to mangrove forest death. Salt marsh (such as *Spartina alterniflora*) will invade habitats of mangrove forests under the effects of global climatic change (SLR) (Zhang et al., 2012; Li et al., 2014). However, carbon sequestration capacity of salt marsh is lower than that of mangrove forests (Alongi, 2014), which will decrease global blue carbon budget. Secondly, soil OC stocks account for the majority of the ecosystem carbon stocks and can even extend several meters in some mangrove forests (Murdiyarso et al., 2015; Chen et al., 2018). Mangrove leaves, roots, wood, microphytobenthos and benthic infauna are the main contributors of soil OC (Kristensen et al., 2008; Bouillon et al., 2008). SLR will increase soil OC stock in mangrove forests (11a-old) in our previous study (Chen et al., 2020b). Mangrove forest became the main contribution of soil OC stock in the mature forests (48 a-old) (Chen et al., 2018). Reduction of mangrove vegetation biomass may decrease soil OC stock which will decrease the whole blue carbon in mangrove ecosystem and be not conducive to climate change mitigation. Finally, *K. obovata is* a native species and is widely used for mangrove restoration in China. SLR effect on the different mangrove species are different and suitable species should be chosen to keep pace with SLR in the future mangrove restoration.

5 Conclusions

The present study showed that long flooding time due to SLR directly decreased mangrove individual density and inhibited the growth of mangrove vegetation. SLR will decrease annual vegetation biomass increment, resulting in the lowest total vegetation biomass and each component biomass at Site SLR 80 cm. Besides leaf, OC content of each component was not affected by SLR while total vegetation OC stock decreased by approximately 3.85 kg/m^2 (in terms of C) from Site SLR 0 cm to Site SLR 80 cm which was related with mangrove vegetation biomass. Therefore, the changes of mangrove vegetation biomass and OC stock could reduce the contribution of mangrove to the atmospheric cooling effect, decrease global blue carbon budget and exacerbate global climate change, which may make a positive response to SLR. Considering the complexity of SLR and different adaptability of different mangrove species response to SLR, long-term observation of mangrove vegetation biomass and OC stock with SLR should be done in the future studies.

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